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The Journal of THE ROYAL AERONAUTICAL SOCIETY

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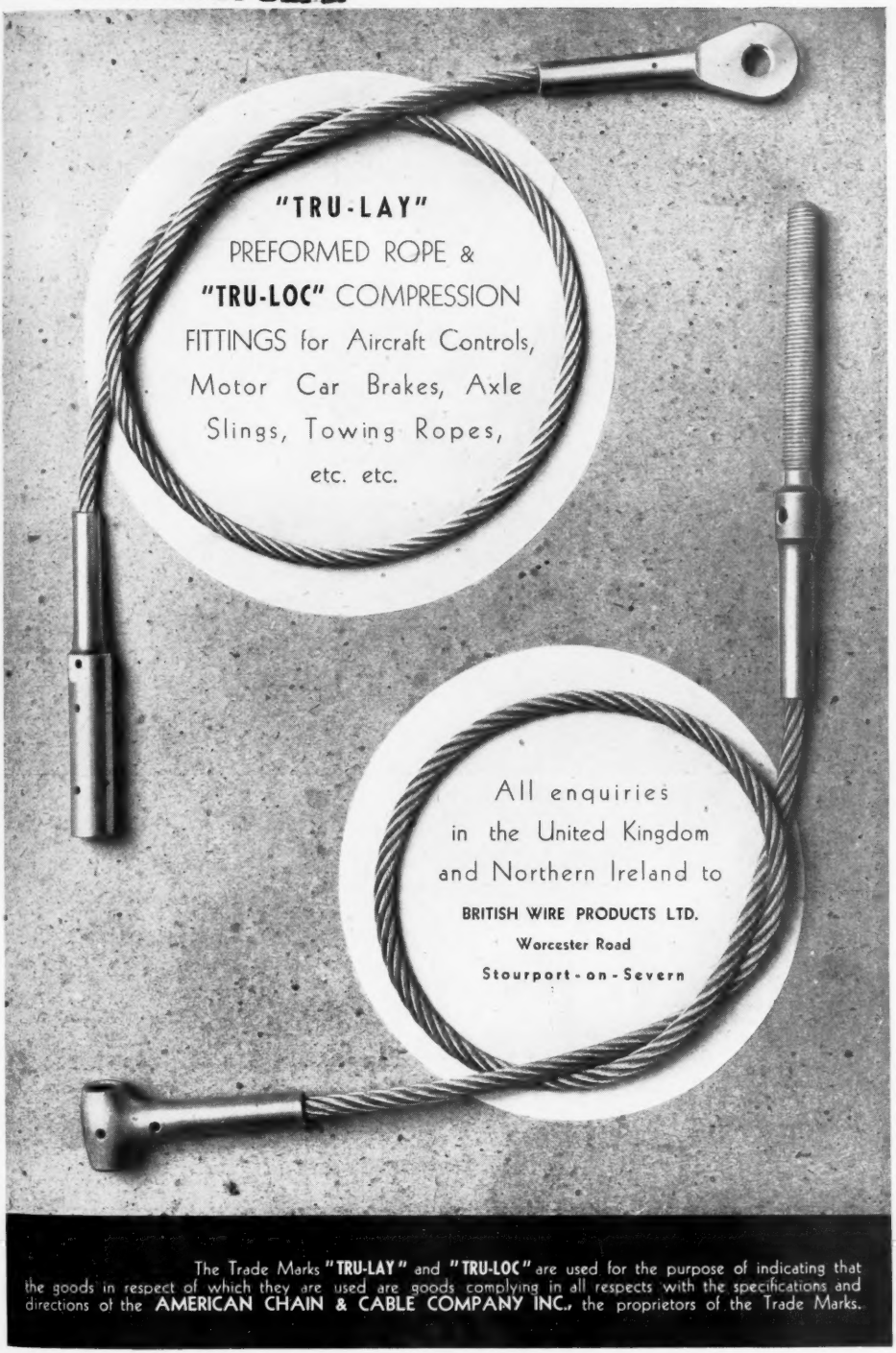

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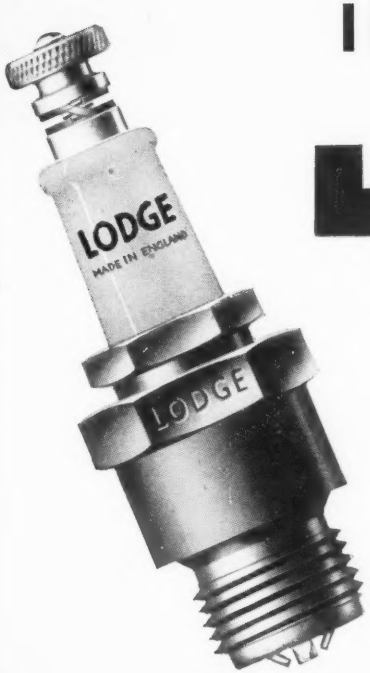

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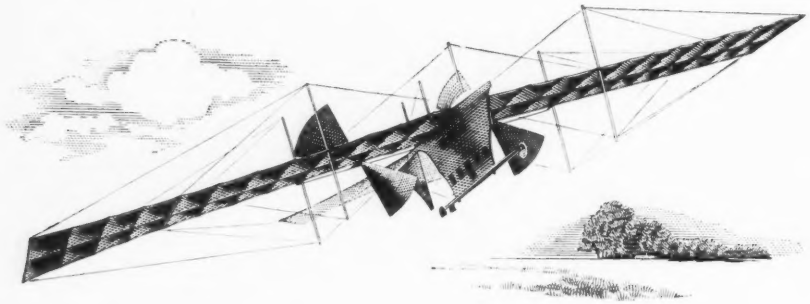
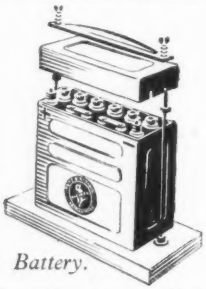


AS HENSON, whose 25-h.p. steam-propelled aeroplane of 1843 is illustrated above, ranked among those who pioneered aviation, so the makers of Dagenite batteries pioneered the construction of AIRCRAFT ACCUMULATORS. To-day, because they embody the results of a rich experience, Dagenite batteries are an essential of the most modern aircraft.



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THE SOCIETY'S PRIZES

The Society offers a number of valuable prizes, most of them annually. Full particulars of the conditions attaching to the awards of these prizes may be obtained on application

Society's Gold Medal

This is the highest honour which the Society can confer for work of an outstanding or fundamental nature in aeronautics.

British Gold Medal for Aeronautics

The British Gold Medal for Aeronautics is awarded for an achievement leading to advancement in aeronautical science.

Simms Gold Medal

The Simms Gold Medal is awarded annually for the best paper read in any year before the Society on any science allied to aeronautics, e.g., meteorology, wireless telegraphy, instruments.

The George Taylor (of Australia) Gold Medal

The Taylor Gold Medal is awarded annually, at the discretion of the Council, for the most valuable paper submitted or read during the previous session.

Wakefield Gold Medal

The Wakefield Gold Medal is awarded annually to the designer of any invention or apparatus tending towards safety in flying, and is open to members or non-members.

Society's Silver Medal

The Society's Silver Medal is awarded, at the discretion of the Council, for some advance in aeronautical design.

British Silver Medal for Aeronautics

The British Silver Medal for Aeronautics is awarded for an achievement leading to advancement in aeronautical science.

Society's Bronze Medal

The Society's Bronze Medal is awarded, at the discretion of the Council, under the same conditions as those for the Silver Medal, but for some less important advance in aeronautical design.

Wilbur Wright Memorial Premium

The Wilbur Wright Memorial Lecture is held annually, a premium of fifty pounds being awarded to the lecturer invited by the Council to deliver the lecture. The lecture is usually given alternately by an American and an Englishman, and is the most important aeronautical lecture of the year. It is delivered whenever possible, on the last Thursday in May of each year.

British Empire Lecture

The Council of the Royal Aeronautical Society have completed the arrangements for the founding of a British Empire Lecture.

The lecture, on any aeronautical subject approved by the Council, will be delivered annually in September in London, by a lecturer, chosen in alternate years from the British Dominions and Colonies and Great Britain.

The Council, by founding this British

Empire Lecture, are anxious to encourage new ideas and new points of view from all parts of the British Empire, and to make the Lecture second only in importance to the Wilbur Wright Memorial Lecture.

The British Empire Lecture will have a premium of £50 attached to it, and in the case of lecturers coming from the Dominions and Colonies an allowance up to £100 will be paid towards the Lecturer's expenses.

It is proposed to hold the first lecture in September, 1945, and suggestions for lecturers should be received by May 31st, 1945, at the latest.

R.38 Memorial Prize

The R.38 Memorial Prize is offered annually for the best paper received by the Society on some subject of a technical nature in the science of aeronautics, preference being given to papers which relate to airships. The prize is twenty-five guineas.

The Herbert Akroyd Stuart Lectures

Under the will of the late Mr. Herbert Akroyd Stuart a sum of £700 is held in trust by the Society for the offer of a prize every two years, for the best paper or lecture read or given before the Society dealing with the Origin and Development of Heavy-oil Aero Engines. The prize is open to members and non-members.

Edward Busk Memorial Prize

The Edward Busk Memorial Prize is offered annually for the best paper received by the Society on some subject of a technical nature in connection with aeroplanes (including seaplanes). Its value is twenty guineas.

Pilcher Memorial Prize

The Pilcher Memorial Prize is offered annually, at the discretion of the Council, for the best paper by a Student on heavier-than-air craft or any analogous subject. Its value is five guineas.

Usborne Prize

The Usborne Prize is offered annually, at the discretion of the Council, for the best paper by a Student on some subject in connection with Aero Engines. Its value is five guineas.

Major Baden-Powell Memorial Prize

The Major Baden-Powell Memorial Prize is awarded in May and December of each year to the student who is considered the best student by the examiners in the Society's Association Fellowship examinations. Its value is three guineas.

Elliott Memorial Prize

The Elliott Memorial Prize is awarded twice yearly to the apprentice at Halton who has the highest percentage of marks in the passing-out examination. Its value is 2½ guineas for each award.

R. P. Alston Memorial Prize

The R. P. Alston Memorial Prize is awarded to any Graduate or Student of the Society for work done leading to improvement in the safety of aircraft, and particularly for improvement in stability and control. Its value is approximately £5.

Branch Prize

The Council offer an annual prize of twenty guineas for the best paper read before the Branches during the previous lecture Session. The prize is open to any member of the Society or of any Branch.

Journal Premium Awards

The Council has set aside an annual sum of £250 to be given as premium awards to authors of papers published in the Journal.

AN APPRECIATION

The Council of the Royal Aeronautical Society wish to thank those Companies who, by their generous co-operation, have done so much to help in the production of the Journal in its new form.

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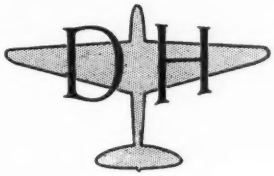

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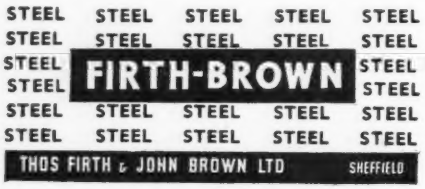

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THE JOURNAL OF
THE ROYAL AERONAUTICAL SOCIETY

With which is incorporated The Institution of Aeronautical Engineers

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The Journal of The Royal Aeronautical Society was founded in 1897 in succession to the Annual Reports. For the opinions expressed in Papers that are signed or initialled the authors alone are responsible. None of the papers or paragraphs must be taken as expressing the opinion of the Council of The Royal Aeronautical Society unless such is definitely stated to be the case. **The Journal is published monthly at the Offices of the Society, 4, Hamilton Place, Piccadilly, London, W.1.** Subscriptions per annum, £4 10 0 post free; Single Numbers 7/6 or 7/9 post free. All communications for publication in the Journal, or on general matters affecting the Society should be addressed to—The Secretary, J. Laurence Pritchard, 4, Hamilton Place, W.1. The Society's Bankers are Messrs. Coutts and Co. All communications respecting Advertisement matters should be addressed to—The Advertisement Manager, Journal of The Royal Aeronautical Society, 4, Hamilton Place, W.1.
Telephone: Grosvenor 3515-3516-3517. Telegraphic Address: Didaskolas, Audley, London.

AUGUST NOTICES 1945

JOURNAL PREMIUM AWARDS

The Council have set aside an annual sum of £250 for the award of premiums for papers published in the *Journal* and the Council hope that members will contribute papers on their own special subjects.

Contents of the August Journal

Control Surface Design, by M. B. Morgan and H. H. B. M. Thomas.

British Empire Lecture

The first British Empire Lecture will be given in November by Mr. Hudson Fysh, Managing Director of Qantas Empire Airways, Limited, Australia. The Lecture will deal with the Past, Present and Future of the route to Australia.

Editor of the Journal

Applications are invited for the post of Editor of the Journal and other publications of the Society. Please give full particulars of experience, etc., to the Secretary.

Honours

The President and Council wish to record their congratulations to two members of the South Africa Branch who received honours recently as follows:—

New Year Honours—

M.B.E. awarded to Lieut.-Col. G. A. Mann, Associate Fellow.

Birthday Honours—

M.B.E. awarded to Major R. A. Powell, Associate Fellow.

Derby Branch

Lectures by the following have been arranged and will be held in the Rolls-Royce Welfare Hall, Nightingale Road, Derby:—

September 3rd—Lord Brabazon of Tara, M.C., P.C., F.R.Ae.S. (Past-President of the Society).

October 1st—Dr. H. Roxbee-Cox, B.Sc., D.I.C., F.R.Ae.S. (Chairman, Power Jets, Ltd.).

November 5th—Air Commodore Vernon Brown, C.B., O.B.E., M.A., F.R.Ae.S., and Wing Commander N. G. Bennett, M.B.E. (Air Ministry Accidents Investigation Branch).

December 3rd—Annual General Meeting.

Acknowledgments

The Council acknowledge with thanks the gift of Journals and other publications from the following:—Wing Commander R. H. Stocken, Fellow; Mr. H. H. Smith, Associate Fellow; Captain E. W. Percival, Fellow.

Election of Members

The following Members were recently elected:—

Associate Fellows

Ralph Hawarden Anderson (from Graduate), William Harley Arklay, George Henry Macmillon Birkbeck (from Graduate), Ernest Geoffrey Collinson (from Graduate), Thomas Yates Cordiner, John Owen Parker Dibbs (from Graduate), James Herbert Harper, John Nelson Dundas Heenan, John Hawke Horsfield (from Graduate), J. Korab-Rulikowski, Thomas Fulton Coleman Law-

rence, Anders Mathisen, Arnold William Morley, Frederick Reginald Murray (from Graduate), Leslie Alfred Phillips, Frank Stanley Saunders (from Associate), Frank Alastair Wadsworth, John William Woodcock (from Graduate).

Associates

Eric Hamilton Batty, Arthur Ronald Boardman, John Talbot Bowe (from Companion), Richard Brett, Beric James Callingham, Norman Leslie Claxton, Charles Victor Cooley, John Edward Cregier, Wilfred Dixon, Frank Doyle, Eric Callwell Ferguson, Goddard Hooker Fretton, Stanley George Giles, Samuel Musgrove Howes, Percy Allardyce Hudson, Robert Frederick Hunt, Edward George Lucas, Stanley Victor Maddox, Sydney John Patmore, Alfred Frank Phillips, Owen Frederick Phoenix, Gilbert Charles Riall, Tom Smith, Gerald Smith, Holbrook Snyder, Leonard Edgar Charles Stewart, William James Swift, James Richard Talbot, Maung Tin Thein, Francis Philip Whaley (Ex-Student), Glynn Lionel Williams, Hugh Joseph Wilson, Francis Ian Hamilton Wood, Henry Ward Beecher Wright, James Walter Scott.

Graduates

Robert Bridge, Frederick Brian Butler (from Student), Neville Lewis Fakes, Jack Dickeson Dodds, Osama Amin El-Kholi, Jack Arthur Froude, Louis Maurice Gardiner, Kenneth George Hancock, Barry Pemberton Leight, Yousef Lotfy, Fahim Lotfy, Robert Maine (from Student), Roland Matthew Morton, Elisabeth Constance Pike (from Student), Hubert Arthur Reid (from Student), Walter Frederick Shilling, Donald Frederick Harvey Rushton (from Student), Francis Alec Williams, Vicor Willis (from Student), Dennis Wright (from Student).

Students

Arthur Paul Britton, Brian Harry Cox, John Samuel Crossley, Alan Robert Daffey, John Harold Drake, Peter Frederick Norman Edwards, Reginald Arthur Fidler, Cyril Fleisher, Peter Michael Gray, Peter David Hall, Cyril Jones, David Aubrey Jones, John Francis Martin, James Gordon Mason, Peter Gilbert Mills, Peter Edward Radcliffe (from Companion), Michael William Salisbury, Peter John William Tuffs, Bernard Guy Webb, Colin Ronald Haigh Wood.

Companions

Charles Dudley Anderson (from Student), Edward William Fidler (from Student), Albert Robert John Winn.

Additions to the Library

Pamphlets in italics with location reference following in brackets. Books marked * or ** may not be taken out on loan.

A.a.313.—*Note on the Calculation of the Critical Speed of Cantilever Wings under Flexural and Torsional Vibrations. G. A. G. Schepisi.* (*R.T.P. Trans. No.* 1025, *from Aerotecnica, Nov./Dec.*, 1939.) (Y.1.a.18.)

A.b.78.—*On the Flow of Compressible Fluid around a Circular Cylinder. E. Pistolesi.* (*R.T.P. Trans. No.* 1027, *from Aerotecnica, Nov./Dec.*, 1939.) (Y.1.c.8.)

A.d.29.—*Study of a High-Speed Wind Tunnel Working by Ejection, with a Steam Jet as the Impelling Fluid. L. Poggi.* (*R.T.P. Trans. No.* 1026, *from Aerotecnica, Nov./Dec.*, 1939.) (Y.1.d.8.)

B.a.336.—*Consolidated Liberator, B-24.* (*Press Release*, 31/5/45.) *Consolidated Vultee Aircraft Corporation.* (Y.3.ii.C.)

B.a.337.—*Shetland Flying Boat.* (*Press Release*, 17/5/45.) *Ministry of Aircraft Production.* (Y.3.iii.34.)

B.a.338.—*Westland Welkin Fighter.* (*Press Release*, 28/6/45.) *Ministry of Aircraft Production.* (Y.3.iii.35.)

B.a.339.—*Gloster Meteor Jet Fighter.* (*Press Release,* 12/7/45.) *Ministry of Aircraft Production.* (Y.3.iii.36.)

B.g.145.—Aircraft of the United States. (Vol. 1.) R. A. Saville-Sneath. Penguin Books, 1945. 5/-.

BB.f.59.—*Instruction Booklets: Kollsman Engine-Speed Indicator, Mks. IV and V; Rate of Climb Indicator, Mk. IB; Sensitive Altimeters, Mks. XIVA, B, B (PC) and C(P); Generator, Mk. IV.* (*File Case.*) *Kelvin, Bottomley and Baird, Ltd.,* 1945. (*File Case.*)

D.b.235.—*The Shipper Looks at Air Cargo. Reprint from "Air Transportation." George S. May Business Foundation, Report No.* 161. 1945. (Y.6.ii.b.33.)

D.d.28.—*Handley Page Training Courses for Aeronautical Engineer Apprentices. Handley Page, Ltd.,* 1945. (PE.b.21.)

E.a.13 and 14.—Aeronautics: A Book of Graded Worked Examples. Vol. 1. (Aerodynamics, the Aero Engine); Vol. 2 (Properties of Materials, Strength of Materials, Structures). J. D. Haddon. Pitman. 1945. 8/6 each.

E.b.107.—Waveform Analysis. R. G. Manley. Chapman & Hall, 1945. 21/-.

E.f.108.—Luftfahrt-Lehrbücherei, Band 1. Die Wartung des Flugzeuges. H. Grube. Matthiesen & Co., Berlin. 1941.

E.f.109.—Luftfahrt-Lehrbücherei, Band 8. Der Flugmotor. Teil II: Die Wartung des Motors. G. Ulsman. Matthiesen & Co., Berlin, 1940.

EE.b.82.—*Gipsy Major* 1500-*hour Overhaul Period. De Havilland Aircraft Co.* (*Stencil*), 1945. (Y.7.d.D.)

*G.a.72 and 73.—Metallurgical Abstracts, Series II, Vols. V (1938) and X (1943). Institute of Metals.

G.e.D.25.—*Conolite: A New Plastic Laminate.* (*Press Release,* 31/5/45). *Consolidated Vultee Aircraft Corp.* (Y.13.c.P.)

*H.b.89.—Shawcross and Beaumont on Air Law. C. N. Shawcross and K. M. Beaumont. Butterworth & Co., 1945. 60/-.

L.a.49.—*Rediffusion Trainer.* (*Stencil Notice.*) *Ministry of Aircraft Production,* 1945. (Y.15.i.b.9.)

L.c.27.—*Test Flying. S/Ldr. J. R. Tobin.* (*Reprint from R.Ae.S. Journal, June,* 1945. (PL.1.a.9.)

**OO.118.—*Minutes of Aviation Industry Forum Meetings on Air Commerce and Airport Problems,* 1944-45. *New York Board of Trade,* 1945. (File Case.)

OO.119.—*Report of Conferences on Standardisation of Screw Threads and Cylindrical Fits. Combined Production and Resources Board,* 1944. (PG.1/27.)

P.c.47.—*Abstracts of Diamond Tool Patents. P. Grodzinski and W. Jacobsohn. Diamond Trading Co.,* 1945. (Y.9.P.)

*Q.a.162.—*Catalogue of Books and Periodicals in Engine Division Technical Library. Bristol Aeroplane Co.,* 1945.

S.d.92.—Air Power for Peace. Eugene E. Wilson. McGraw Hill, 1945. $2.

S.e.84.—Arnhem Lift—the Story of a Glider Pilot. Pilot Press, 1945. 5/-.

S.e.85.—His Majesty's Submarines. Ministry of Information. H.M.S.O., 1945. 9d.

TT.a.48.—From the Earth to the Moon. Jules Verne. Sampson Law, Marston & Co., 1888.

*UF.9/19.—*Service Technique de l'Aéronautique, Bruxelles. Bulletin No.* 19. Sur quelques problèmes de la Théorie Tourbillonnaire de l'Hélice Propulsive et de l'Aile d'Avion. N. Florine. 1944.

*X.e.55.—Who's Who in (American) Aviation. U.S. Works Projects Administration. Ziff Davis Publishing Co., New York, 1942. $5.

*UU.c.—*National Advisory Committee for Aeronautics (U.S.A.). Technical Memoranda: No.* 1082. Recent Development of the Two-Stroke Engine. (II) Design Features. J. Zeman. (R.T.P.3 Trans. 2382 from V.D.I., Vol 87, No. 13/14, 3/4/43.)

J. LAURENCE PRITCHARD,
Secretary

M. B. Morgan

CONTROL SURFACE DESIGN

in Theory and Practice

by

M. B. Morgan, M.A., F.R.Ae.S.,

and

H. H. B. M. Thomas, B.Sc., A.F.R.Ae.S.

M. B. Morgan studied under Sir Melvill Jones at Cambridge, taking 1st Class Honours in the Mechanical Science Tripos, 1934, and obtaining the Seely prize in Aeronautics.
Apprenticed with Vickers and Mather & Platt, Ltd., he joined the Aerodynamics Staff at R.A.E., Farnborough, in 1935, as a junior Scientific Officer. He is now principal Scientific Officer, covering Flight Tests on Stability and Control.

A MEETING of the Royal Aeronautical Society was held in the lecture hall of the Institution of Mechanical Engineers, Storey's Gate, St. James's Park, Westminster, London, S.W.1, on Thursday, March 1st, 1945, at which a paper on "Control Surface Design in Theory and Practice" was read by Mr. M. B. Morgan, M.A., F.R.Ae.S., and Mr. H. H. B. M. Thomas, A.F.R.Ae.S.

In the chair, the President, Sir Roy Fedden, F.R.Ae.S.

THE CHAIRMAN welcomed the authors as representing the younger generation in aeronautics. Both Mr. Morgan and Mr. Thomas were actively engaged in the investigation of the subject on which they were now lecturing, and he felt that we should now hear an accurate and interesting lecture.

H. H. B. M. Thomas

H. H. B. M. Thomas obtained 1st Class Honours in Mathematics at the University of Wales and joined the Staff of R.A.E. in 1940.
He is now a Scientific Officer in the Aerodynamics Department engaged on Theoretical Stability and Control Research.

CONTROL SURFACE DESIGN

1. *Introduction*

EXPERIENCE during the war has shown clearly that, of the major aerodynamic problems facing the designers of military aircraft, the production of satisfactory control surfaces is one of the most intractable. Indeed, many take the line that control surface design is still far more of an art than a science. Considerable sympathy must be felt for this view, since it is fair to say that the difficulties of this subject have mounted so rapidly with the increase of speed and size of modern aircraft, and with the increasing severity of operational requirements, that research has been hard put to it merely to keep abreast of modern developments, let alone get ahead of them. Nevertheless, it is thought that many of the difficulties at present encountered arise from a lack of full appreciation of existing information on control power and balance. The reason for this is fairly obvious. Such information is widely scattered in hosts of theoretical, wind-tunnel and flight reports. Much of it requires very critical examination; for example, tunnel tests at unduly low Reynolds numbers or with unknown transition conditions can give highly misleading results, particularly on hinge moments. If the technician dips at random into the pile of reports on his desk he is quite likely to get such conflicting answers that he gives the whole thing up as a bad job, and falls back on intuition and rule of thumb in proportioning his controls—often with unfortunate results.

In Part I of the present lecture a few of the design problems common to all three controls are considered; there follows a discussion of the difficulties associated with each individual control—ailerons, elevator and rudder—while the problem of controlling the very large aircraft is also touched upon. Part II contains an outline of our present knowledge of control power and balance, and the way in which theory is being developed to explain recent wind-tunnel results is described. Finally, in Part III, a few concluding remarks are made on prototype testing.

Paper received February, 1945.

PART I—PRACTICE

2. *Preliminary Statement—Problems Common to all Three Controls*

2.1. *Objectives*

It will be well at the outset to clear our ideas on just what we expect of the primary flying controls. The popular statement that the purpose of the controls is " to enable the pilot to impose his will on the aeroplane " does not stand examination without drastic qualification. When a pilot emerges from thick cloud only to be confronted by a hillside, he quite naturally desires to come to an abrupt halt in mid-air; the fact that on a conventional machine he is unable to gratify his desire does not imply (with all due respect to helicopter enthusiasts) that the controls are inadequate. The behaviour of an aeroplane is bounded by some quite definite technical limitations; if airspeed is reduced below a certain value the machine stalls; for a given aileron angle, other things being equal, the steady rate of roll is roughly proportional to the true airspeed and inversely proportional to the wing span; for a given geometry the aerodynamic hinge moment on a control surface increases as the square of the indicated airspeed and as the cube of the linear dimensions; and so on. The aim of the designer must be so to proportion his controls that the pilot can, within the framework of the above technical limitations, execute without fatigue or discomfort those manœuvres which are necessary for the aeroplane to fulfil satisfactorily its function —either civil or military.

Many of these necessary manœuvres are common to both civil and military types; take-off and landing, correction of trim on altering throttle, flap and undercarriage position, controlling a multi-engined aircraft with one engine dead, etc., are obvious examples. Manœuvres of the type involved in violent evasive action at high airspeeds

are, however, peculiar to military machines. Since, in general, ability to manœuvre violently at high speeds when in combat demands controls with a higher degree of balance than would be needed for normal flying, the design problems associated with the controls are more severe on military than on civil aircraft, size for size. In what follows, particularly in those sections dealing with balance, emphasis will thus be placed upon the design of controls for aircraft such as fighters and bombers.

2.2. *The Pilot*

From the technician's viewpoint the most obvious problem common to all three controls is the pilot. The designer can produce things that fly with a very wide variety of speeds, sizes and shapes; theoretically there are many ways of applying controlling moments to an aircraft, ranging from the conventional moving surface at the trailing edge to spoilers and suction devices; but in all cases we have as a common factor the man whose job it is to sit in the middle of the contraption, taking immediate responsibility for its conduct—to wit, the pilot.

Since we are interested in military aircraft we may take as our hero F/O. Fearnaught-Smith, the average service pilot. To the industry, Fearnaught's best known characteristic is his weight—in flying kit and with parachute he has for years scaled precisely 200 lb. We are here, however, more concerned with what he can do with his arms and his legs. Taken in bulk, pilots vary considerably one from the other, but in relation to the enormous variations possible in the control forces and movements which a designer can give to an aeroplane, such differences from the average are small and need not worry us; they can be met by relatively small adjustments of seat or pedal position. Again, the well-known N.A.C.A. series of tests in a ground rig have established the way in which a pilot's efforts vary with fore-and-aft and sideways position of the stick grip or wheel, and with fore-and-aft rudder pedal position. We will here assume that the pilot is sitting with his harness done up and with the controls placed in a conventional position in relation to the seat. Experience then suggests that Fearnaught-Smith's characteristics are roughly as given in Table I.

In compiling this table we have drawn largely on experience gained during flight tests of a wide variety of aeroplane types which have been fitted with stick and pedal force indicators for various handling research programmes. It should be noted that no attempt has been made to differentiate between the pilots of large and small aircraft, apart from the distinction made between the stick and the wheel types of control. This lack of differentiation is deliberate, since it seems quite illogical to imagine that the bomber pilot is a man of much more powerful physique than the fighter pilot, and can therefore be expected to exert himself more heavily than the pilot of a smaller aircraft during normal manœuvres for an equal amount of fatigue. The control balance problem admittedly becomes much more acute as aircraft size go up, while structural factors of safety admittedly come down. Nevertheless, there has in the past been a strong tendency to provide pilots of large aircraft with controls far heavier than was warranted on grounds of structural safety, and the pilots have not complained over loudly because they have rarely known anything better. With increasing knowledge of balance characteristics, and in particular with the advent of the spring tab and power operation, it should be possible to improve considerably on this situation. It is therefore suggested firmly that in setting out our design cases for controls, we should take as our basis the single average pilot of Table 1, whether the aeroplane be large or small.

The points raised in the above table may be enlarged upon. Case 1, the all-out effort, is largely academic; under no circumstances when flying is it legitimate to demand such an effort, even in an emergency. Case 2 in

TABLE I

CHARACTERISTICS OF AVERAGE PILOT

No.	Case.		Ailerons (sideways or peripheral force).		Elevator (push or pull).		Rudder (push).
			Stick.	Wheel.	Stick.	Wheel.	
1	Greatest all-out effort of which he is physically capable for a very short time (two hands) (lb.)		90	120	180	220	400
2	Maximum force it is permissible to demand of him for short while (lb.)	a. 2 hands	–	80	100	110	200
		b. 1 hand	50	50	70	70	
3	Greatest force he cares to exert for a short while (lb.)	a. 2 hands	–	30	–	40	60
		b. 1 hand	20	20	30	30	
4	Largest hand or foot movement to which he is accustomed for full control travel		±10″	±20″	±9″	±9″	±5″
5	Smallest time, from the initiation of the control movement, in which he can reasonably be expected to apply full control. Forces as in 3		¼ sec.	½ sec.	Not applicable		½ sec.
6	Reaction time, i.e., time-lag between the occurrence of an unexpected event and the instant when the pilot starts taking corrective action on the controls		Anything up to 3 seconds				

no way represents the desirable upper limits for pilot's effort. The figures quoted represent the maximum exertions it is permissible to demand of a pilot in any circumstances; if he is forced to use larger forces than these the controls should be deemed unacceptable. Case 3 is highly important, setting out as it does the highest forces which a pilot cares to exert either in normal circumstances (take-off and landing, lowering flaps, combat manœuvres, etc.) or in abnormal circumstances (engine cut, baulked landing, etc.). The values chosen are very much a matter of opinion, but are thought to represent fairly what a service pilot would like the designer to achieve in the way of upper limits. It should be stressed that these figures of case 3 are *upper* limits—the pilot would frequently like something less—yet in practice they are often not met. It would be a sound design policy to aim at beating these limits for all the manœuvres which may legitimately be demanded of a type; unless, from considerations of structural safety, there is a strong argument, in any particular case, for forcing the pilot to put up with higher loads.

Case 4, maximum hand and leg movements, plays a major part in setting extremes

to the mechanical advantages between the pilot's controls and the control surfaces, i.e., to the stick and pedal gearings. It should again be noted that the figures quoted are *maximum* values, above which the pilot would feel that he was being asked to work his hands and feet through excessive distances; on most existing aircraft the greatest movements provided are distinctly less. It is difficult to generalise about the optimum, as distinct from the maximum allowable, values for these distances.

The contrast between cases **5** and **6** is of interest, indicating that in a sudden and unexpected emergency, an engine cut on a multi-engined aeroplane is a typical case, the time taken for the pilot to react to the situation may well exceed the subsequent time he takes to apply the necessary control. This has an important bearing on any theoretical analysis of the motion following an engine cut.

Finally it should be noted, comparing cases **1** and **3**, that the all-out loads a pilot is capable of exerting are of a much higher order than those considered desirable when manœuvring. Hence, if the controls are reasonably light for normal flying, it is usually within the physical compass of the pilot to break the aeroplane by mis-use of the controls. Conversely, should the controls be made so heavy as to make it impossible for the pilot to overstrain his aircraft, they would be unacceptably heavy for normal manœuvres. This point will be enlarged upon later in para. **3.2** when elevator design is being considered.

We have spent some time on the pilot since his characteristics form an essential part of any discussion about control balance. Technicians, immersed in b_1's, b_2's, tail volumes and the like, sometimes let the pilot drift too far into the background; his physical capabilities and preferences should be kept in the forefront of their minds.

2.3. *Harmony*

During the years preceding the present war, the topic of " harmony of the controls " exerted a peculiar fascination upon those of us working in the stability and control field. It was observed that the general handling qualities of a few types of aircraft were almost universally considered excellent by pilots, while again a few other types were generally termed unpleasant—most aircraft, of course, falling somewhere in between; and it was considered, quite reasonably, that one of the main factors behind the pilots' likes and dislikes was likely to be the success with which the controls had been harmonised. The attractiveness of this conception lay in the idea of developing a numerical criterion for " harmony " in the form of a ratio A:E:R representing the relative values of the forces exerted by the pilot at the stick and rudder pedals on ailerons, elevator and rudder during certain specified manœuvres. Possibly a more refined criterion would prove necessary, bringing in the response characteristics. By testing good and bad aeroplanes a fixed value would be established for A:E:R—1:2:4 was a popular guess—and if a designer worked to this he should greatly increase his chance of producing a machine judged by most pilots to have sweet controls.

With the advent of war emphasis rapidly shifted from the question of " niceness " of control; all our attention was focussed on the difficult job of producing controls which really worked at the very high airspeeds which operational experience quickly showed were the rule rather than the exception in combat. It is now common knowledge that at the start of hostilities most of the front-line fighters of the opposing countries, while delightfully pleasant aircraft for general flying and aerobatics, had ailerons which were almost immovable in a high speed dive. The situation at present is that on each control certain exacting design cases, which will be discussed in para. **3**, must be met if the pilot is to be given a reasonable chance of doing his operational job well. Meeting these design cases is a difficult enough

problem, and provided success is achieved harmony can usually be left to look after itself.

As a postscript to this discussion, a recent conversation with a pilot who has done a lot of flying on our latest fighters—Spitfires, Tempests, etc.—during the past few years is relevant. Before the war he was greatly addicted to a certain fighter which was in those days highly esteemed throughout the service. In his view the controls were as near perfection as could be desired. A short while back he had an opportunity of renewing his acquaintance with his old love—one of the type had managed to dodge the scrap heap. He was frankly appalled. The controls seemed heavy and sloppy, harmony was poor—rudder much too light in relation to the other controls, aerobatics felt unpleasant, and so on. All this in an aeroplane which seven or eight years ago he thought had superb handling characteristics.

The moral of this story is that pilots' opinions are not absolute, but change with the progress of technical development. In the possibly somewhat more leisurely times after the war it would seem unprofitable to return to our quest for some absolute formula for " harmony." Rather should we continue to treat each individual control on its own merits, and make quite sure that it is up to its job.

2.4. *Mechanics*

Although strictly speaking outside the scope of the lecture, a word must be said about the importance of good mechanical design of the controls and control circuit. An American designer of very large aircraft once said in this connection that " the mechanics are almost as important as the aerodynamics." Avoidance of backlash and excessive control circuit stretch are obvious points to watch. Owing to its insiduous nature—adding up a little bit here and a little bit there—friction in the circuit can mount to alarming proportions unless careful attention is paid to friction prevention in the design stage. Controls that are impeccable aerodynamically can be ruined by excessive friction; a pilot finds lack of self-centring at low airspeeds extremely irritating. In terms of pilot's force at his controls, every effort should be made to keep the friction on ailerons, elevator and rudder down to something less than 2, 4, and 6 lb. respectively on fighters; the corresponding figures for bombers the size of our present " heavies " may be taken as 8, 10 and 10 lb. respectively.

Avoidance of excessive friction is particularly important in spring tab and pure servo tab designs. With controls of this type there is no rigid connection between the stick and the control surface; as a result friction at the control hinges, say, can produce serious lag in response, in that for small stick movements no corresponding movement of the control surface occurs, whereas for slightly larger movements the control surface suddenly moves as friction is overcome, and the aeroplane responds with a rush. Such a state of affairs can be positively dangerous at low airspeeds on the approach. From the anti-flutter viewpoint designers should also be particularly on their guard against excessive backlash in spring and pure servo tab layouts.

2.5. *" Response Effect "*

" Response effect," sometimes termed the " b_1 effect " by the more learned, is the name given to the alteration in control hinge moment which can arise from the response of the aeroplane to control movement. We will see in Part II that the hinge moment coefficient on a control surface is conveniently written

$$C_H = b_o + b_1\alpha' + b_2\eta \quad . \quad . \quad . \quad (1)$$

where

α' is the local aerofoil incidence

η is the control angle

while b_o, b_1 and b_2 are " constants."*

* The imperfections of the conception of b_1 and b_2 as constants will become obvious on perusal of Part II of this lecture.

The physical significance of b_2 is fairly obvious, representing as it does the rate of change of hinge moment coefficient with control angle at constant incidence; unless the control is basically overbalanced, b_2 is always negative with the usual sign convention (this convention is that control angle is taken as positive in the direction for increasing the lift, while hinge moment is considered positive when it tends to increase the control angle). To the uninitiated the notion behind b_1 requires more careful consideration. b_1 represents the rate of change of hinge moment coefficient with local aerofoil incidence, at constant control angle. Suppose we start off with the control central and the aerofoil at zero incidence, and then we gradually increase the aerofoil incidence. Most controls will, if left free, tend to float along the relative wind; i.e., as incidence is increased, the trailing edge of the control will move upwards. Such a control is said to have a negative b_1. On the other hand, controls with certain types of balance (the unshielded horn balance is the most common example) have the peculiar property of floating *against* the relative wind—as incidence is increased the control tends to move down instead of up. In this case b_1 is positive. Thus, while b_2 is always negative on any well behaved control, b_1 may be either negative or positive, although more usually it is negative.

Now, when the pilot applies a control, the aeroplane responds. To fix our ideas, let us consider the elevator. Suppose the pilot moves the elevator up. The aeroplane will proceed to pitch nose up, and the tailplane incidence will therefore be increased. If the elevator b_1 is negative, the elevator will want to trail up because of this increased tailplane incidence, thereby reducing the pilot's effort needed to hold the elevator up. Conversely, if b_1 is positive, the pilot's effort will be increased. The ratio of pilot's effort allowing for such a "response effect" to what it would be if there were no response is termed the response factor K. In mathematical terms, if a change in elevator angle $\Delta\eta$ produces, owing to response, a change $\Delta\alpha'$ in tailplane incidence, the change in elevator hinge moment coefficient C_H is given by

$$\Delta C_H = b_1\Delta\alpha' + b_2\Delta\eta \quad . \quad . \quad . \quad (2)$$

$$= \left(1 + \frac{b_1}{b_2} \cdot \frac{\Delta\alpha'}{\Delta\eta}\right) \cdot b_2\Delta\eta$$

If there were no response ($\Delta\alpha' = 0$), then

$$\Delta C_H = b_2\Delta\eta$$

Hence the response factor K may be written

$$K = 1 + \frac{b_1}{b_2} \cdot \frac{\Delta\alpha'}{\Delta\eta} \quad . \quad . \quad . \quad . \quad (3)$$

and the pilot's effort, instead of being proportional to b_2, is proportional to Kb_2. Since both $\Delta\alpha'/\Delta\eta$ and b_2 are negative, K is less than unity when b_1 is negative, and response lightens the control forces, as we have already noted; while a positive b_1 means that K is greater than unity, and the control thus feels heavier.

In many cases K is not far from unity; but with certain types of balance giving an unusually large value for b_1/b_2, response can have a profound influence on the "feel" of the controls. In general response effects are more marked on elevator and rudder than on ailerons, since in the case of the former two controls a unit control angle produces larger values for $\Delta\alpha'$ than does application of unit aileron angle. On aeroplanes the size of present day single engined fighters, a typical value for $\Delta\alpha'/\Delta\eta$ (aileron) is 1/5, whereas $\Delta\alpha'/\Delta\eta$ (elevator) and $\Delta\alpha'/\Delta\eta$ (rudder) may well be of the order of 1.0 or more.

With regard to b_1/b_2, the value for this ratio normally lies within the region 1.0 to -1.0 for controls balanced by means other than a geared tab. Larger values can arise with geared tab balance, since in general a geared tab leaves the effective b_1 of the control unchanged, but reduces numerically the value of b_2; if a control has initially a high negative b_1, and a geared tab is used to balance closely on b_2, the ratio b_1/b_2 may rise to about 2.0, with consequent magnifi-

cation of the favourable influence of response on pilot's effort.

As an example of the effect under discussion, some years ago we were puzzled at our pilots' reports that the elevator of the Lockheed 12A, a transport aeroplane of about 350 sq. ft. wing area, was pleasantly light although (i) the aeroplane was quite stable longitudinally and (ii) the elevator was completely unbalanced. A flight investigation showed that the elevator forces when manœuvring were roughly halved owing to response effect, the measured value of b_1/b_2 being about 0.75.

This topic of the interaction between response and hinge moments has been stressed here, possibly at undue length, since when interpreting wind-tunnel results there is sometimes a tendency to argue solely on b_2. Unless b_1 is brought into the picture a misleading impression may well be gained, particularly in the case of elevators and rudders.

2.6. *" Stick-free " Stability*

The sign of b_1, expressing as it does whether the control tends to trail along the relative wind or against the relative wind, must obviously determine whether stability is increased or decreased on freeing the control surface. Consider once again the tailplane and elevator. The lift coefficient of the tail may be written

$$C_L' = a_1\alpha' + a_2\eta \quad . \quad . \quad . \quad . \quad (4)$$

α' and η being as before local tail incidence and elevator angle, while a_1 and a_2 are constants.

If a gust suddenly pitches the aeroplane, the tailplane will tend to restore the aeroplane to its original attitude because the change of tail incidence, $\Delta\alpha'$ will produce a change in tailplane lift coefficient $\Delta C_L'$, thereby giving a restoring moment about the centre of gravity (this moment will be of no avail if the aeroplane is unstable owing to the C.G. being too far aft, since in this case the destabilising wing and body moments overpower the stabilising tail moment).

Consider now what happens if (i) the elevator is rigidly fixed at some constant angle, and (ii) the elevator is left absolutely free to rotate, so that $C_H = 0$ throughout. In the first case the change in tail lift coefficient resulting from the tail incidence change $\Delta\alpha'$ must, from equation (4), be

$$\Delta C_L' = a_1\Delta\alpha' \text{ " stick fixed " } . \quad . \quad (5)$$

whereas, in the second case, with the elevator free, the elevator will trail through an angle $\Delta\eta$, and the change in lift coefficient will be

$$\Delta C_L' = a_1\Delta\alpha' + a_2\Delta\eta$$

and, since $C_H = 0$ throughout, we have from equation (2)

$$\Delta\eta = -b_1/b_2\Delta\alpha'$$

Thus

$$\Delta C_L' = a_1\Delta\alpha'(1 - a_2b_1/a_1b_2) \text{ "stick free" } (6)$$

Comparing equations (5) and (6), it can be seen that the stabilising force produced by the tail is modified in the ratio $(1 - a_2b_1/a_1b_2)$ on freeing the elevator. The term a_2/a_1b_2 is always negative. Hence a " negative b_1 "—possessed normally by unbalanced or moderately balanced set back hinge controls—will give a value less than unity for $(1 - a_2b_1/a_1b_2)$ and will result in a loss in stability on freeing the stick—as is obvious physically, since the control tends to float along the wind, so reducing the lift—whereas a positive b_1, often possessed by unshielded horn balance, etc., will result in a gain in stability on freeing the control. Similar arguments to those given above for longitudinal stability also apply to the contribution of fin and rudder to weathercock stability, while the effect of freeing the ailerons on rolling moment due to sideslip can also be considered in the same way.

For both the tails and fins of conventional aeroplanes the ratio a_2/a_1 does not vary greatly from type to type, in comparison with the large range from positive to negative possible for b_1/b_2. Hence the difference between control fixed and control free stability depends primarily on the ratio b_1/b_2, which makes it a very important parameter to the designer.

It is quite true that the notion of a control surface being " fixed " or " free " does not bear much relation to what goes on when a pilot is flying an aeroplane. He normally rests his hands and feet quite lightly on the stick and rudder pedals, which are thus usually neither fixed nor free. They are certainly very rarely fixed—the conception of a pilot clamping the stick or rudder pedals in one position is quite unreal—although more often they are released, particularly the rudder pedals. Quite apart from this, however, the state of the control surface may not be closely related to what a pilot is doing with his stick in the cockpit. For example, if there is considerable friction in the circuit at or near the elevator hinges, the elevator may itself be effectively fixed during a phugoid oscillation, although the pilot has freed the stick; again, if there is little friction but considerable backlash or slackness in the circuit, the pilot may do his best to hold the stick fixed and yet leave the elevator effectively free for small movements.

For these reasons many people, pilots in particular, are inclined to look on the conceptions of " stick fixed " and " stick free " stability as rather rarified ideas adopted by impractical technicians who should know better. This attitude arises from a misunderstanding of technical jargon. When the scientist talks about " stick free " and " stick fixed " stability he is really discussing certain fundamental aerodynamic characteristics of the aeroplane from which can be deduced features of the utmost practical importance to the pilot. As an example, the " stick free " longitudinal stability characteristics largely determine the stick force needed to change the speed of the aeroplane without retrimming, while from the " stick fixed " longitudinal stability characteristics the stick movement needed to make this speed change can be deduced. The significance of h_1/h_2 is thus by no means academic, and one of the main arts of elevator and rudder design lies in suitably adjusting this ratio.

2.7. *Increased " Liveliness " of Control with Height*

This effect has only become of importance in recent years, accompanying the marked increase of operational heights—fighters nowadays regularly flying higher than what was a world record for altitude a decade or so ago. Pilots are often rather puzzled by the physical ideas behind increased " liveliness " at altitude, and sometimes interpret it as instability.

Briefly, at a given A.S.I. reading, ignoring for simplicity any Mach number effects, the applied moment on an aeroplane resulting from application of a certain control angle is independent of height, being determined solely by V_i^2. The damping moment, however, which comes into play when the aeroplane attains an angular velocity, falls off with height. Hence the aeroplane responds more briskly at high altitudes.

This can best be seen from consideration of the ailerons. A given aileron angle will produce a rolling moment proportional to V_i^2. A steady rate of roll will be achieved when the damping moment just balances this applied moment. The damping moment arises from the change in effective wing incidence resulting from the roll; that of the downgoing wing will be increased, and that of the upgoing wing decreased. For a given rate of roll, it is fairly obvious that the change in mean wing incidence on one side is equal to the ratio of downward velocity (determined by rate of roll and span) and forward velocity (i.e., *true* airspeed), and hence is proportional to $1/V$, the resultant damping moment thus varying as V_i^2/V. Hence, considering the balance of the applied moment and the damping moment, final steady rate of roll must be proportional to $V_i^2/(V_i^2/V)$, i.e., to V, the true airspeed. Since $V = V_i/\sqrt{\sigma}$, where σ is the relative density, at a given A.S.I. (i.e., a given V_i) the steady rate of roll will thus be proportional to $1/\sqrt{\sigma}$. Values for this factor are given in the table.

Height, feet.	$1/\sqrt{\sigma}$ = rate of roll at altitude / rate of roll at sea level (Const. A.S.I.)
0	1.0
10,000	1.16
20,000	1.37
30,000	1.63
40,000	2.01
50,000	2.55

It will be seen that below 20,000 ft. the effect is not very pronounced, but above that height it starts becoming noticeable; at 40,000 ft. rate of roll is roughly double that obtainable at low altitudes at the same A.S.I. reading.

Similar arguments, though different in detail, hold for the response to elevator and rudder. This increased control liveliness plays a part in the sensation of " balancing on a pin point " often reported by pilots at very great heights, although other factors such as lack of power reserve undoubtedly also come into the story.

2.8. *" Repeatability "—Role of the Spring Tab*

2.81. *Manufacturing Errors and Distortion in Flight*

One of the major troubles facing the designer in connection with the controls of modern military aircraft, large and small, is the great variation in the aerodynamic heaviness of the controls on aeroplanes of the same mark whose geometry is nominally identical. As aeroplanes come off the production line wide differences between the control characteristics of the individual aircraft are often found during the production flight tests, ailerons being the worst offenders, and much effort must be expended, adjusting hinge height, doctoring the profile, or even changing the ailerons at random until a suitable pair is found, in ensuring that each aircraft finally passed out to the surface meets some acceptable standard. The same difficulty arises when damaged controls have to be replaced in service. In aggregate the time wasted owing to this lack of "repeatability" is enormous.

We now have a fairly clear idea of the reasons behind " repeatability " troubles. Basically they have arisen because designers have been forced, during the last few years, to balance their controls much more closely than was usual in the past. Certain classes of aircraft, particularly the " heavy " bombers, have increased greatly in size; on all classes the airspeeds have gone up; and, most important of all, operational requirements have rapidly increased in severity under the spur of competition with an enemy of undoubted technical ability. All these factors have driven designers to exceedingly close balance.

Now the overall hinge moments on a highly balanced control are very sensitive to quite small alterations in its profile shape. The wind-tunnel work at the National Physical Laboratory, to be discussed in greater detail in Part II of this lecture, has shown this clearly; in particular, the trailing edge angle plays a dominating part in determining the variation of hinge moment with control angle and with incidence. Lack of " repeatability " arises from such small alterations in the geometry of the control. These can be classed under two heads, namely:—

(i) Those resulting from errors in manufacture—small differences in profile, hinge height, shroud settings, gaps, etc.; and

(ii) Those resulting from distortion of the control surface under aerodynamic loads, distortions of the covering material being the most important.

The second class, distortion in flight, can be dealt with to some extent by stiffening the control panels. In the case of fabric covering more ribs can be added, venting can be made more definite, etc. Many, however, hold the view, shared by the authors, that metal covering is desirable on any very highly balanced control, although even with metal covering panel distortion at high speeds can produce effects by no means negligible.

Two startling instances of the influence of fabric distortion may be of interest. Both are taken from flight experiments undertaken by Mr. D. J. Lyons at Farnborough. On a large four-engined aircraft the stick force per " g " in the dive was reduced in the ratio 3:1 on changing from fabric to metal covered elevators. While measurements of the hinge moments on a single fabric covered Frise aileron on a Spitfire at various speeds gave the striking results illustrated in Figs. 1 and 2. A rough idea of the trailing edge angle and centre line camber of a section midway between a single pair of ribs was obtained by electrical apparatus inside the aileron. These rough figures for trailing edge angle and camber are plotted, together with hinge moment coefficient, against aileron angle. In Fig. 1 the large change in the character of the hinge moment curve on increasing the speed from 150 m.p.h. to 350 m.p.h. should be noted; the similarity to the hinge moment curves of the trailing edge angle and camber curves shows conclusively that such geometrical changes play a large part in the alteration of the hinge moments. The curves of Fig. 2 apply to the same aileron, the sole difference being that the holes leading to the interior of the aileron at the hinge points were sealed, thereby altering the internal pressure and so changing the distortions. It will be seen, comparing Figs. 1 and 2, that the hinge moment curves are greatly altered by this modification.

The first-class, errors in manufacture, is difficult to cope with. A control surface cannot be built with the precision of a watch. If an attempt were made in manufacture so to tighten up the tolerances that the geometrical differences between individual controls had no appreciable aerodynamic significance, the additional work in the shops would certainly represent an even greater effort than is at present expended in getting the controls " right " by trial and error during the flight tests of each individual aircraft off the production line. Such an approach is therefore uneconomic.

For those who would care to estimate the significance of changes in profile shape in any particular case, the following crude generalisations are given, based on tunnel tests at the N.P.L.

(i) A $\pm$ 1° change in the mean trailing edge angle of the last 10 per cent. of the control chord will result in a change in b_2, Δb_2 of about ± 0.04.

(ii) An increase of the centre line camber of the control of 0.01 will produce a ΔC_H of -0.03.

Experience on " repeatability " to date may be summarised by the statement that if metal covered controls are manufactured with average care, the designer must be prepared for a variation ΔKb_2 of ± 0.05 in the aerodynamic balance factor Kb_2 as between controls made to the same drawings. If we are working to a basic Kb_2 of -0.1, this means a $\pm$ 50 per cent. variation in aerodynamic heaviness. On military aircraft it is often desirable, in the interests of operational efficiency, to give the ailerons an even higher degree of balance than that represented by a Kb_2 of -0.1. When this is done the consequences of a ΔKb_2 of ± 0.05 can easily become unmanageable.

2.82. *Methods of Avoiding the Consequences of Errors in Manufacture*

Two solutions to the problem are available. They are:—

(i) The spring tab.

(ii) Power operation.

Power operation is the obvious answer to " repeatability " troubles. No attempt need be made to give the control a very high amount of balance. An electric or hydraulic engine more powerful than the average pilot is installed to push the control around. The pilot actuates the motor through some follow-up mechanism which provides a control angle proportional to stick angle. If necessary the pilot is given " feel," either by

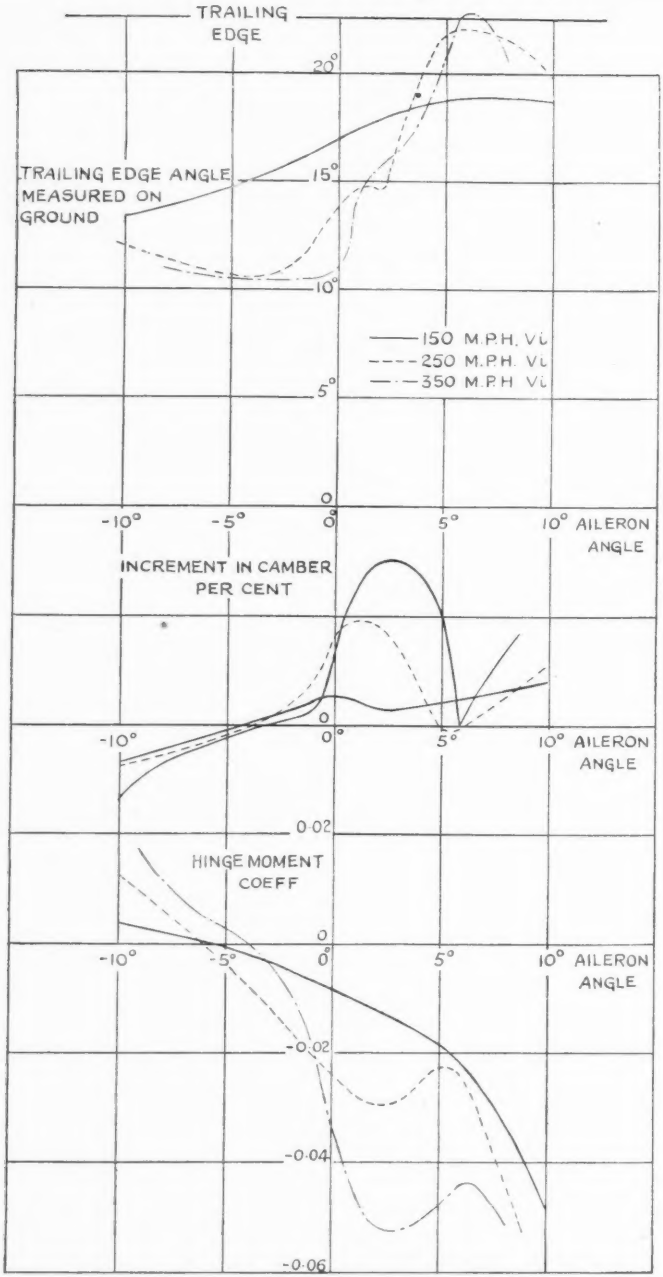


Fig. 1
Comparison of curves corresponding to speeds of 150, 250 and 350 m.p.h. V_i.
Fabric aileron—hinge holes unsealed.

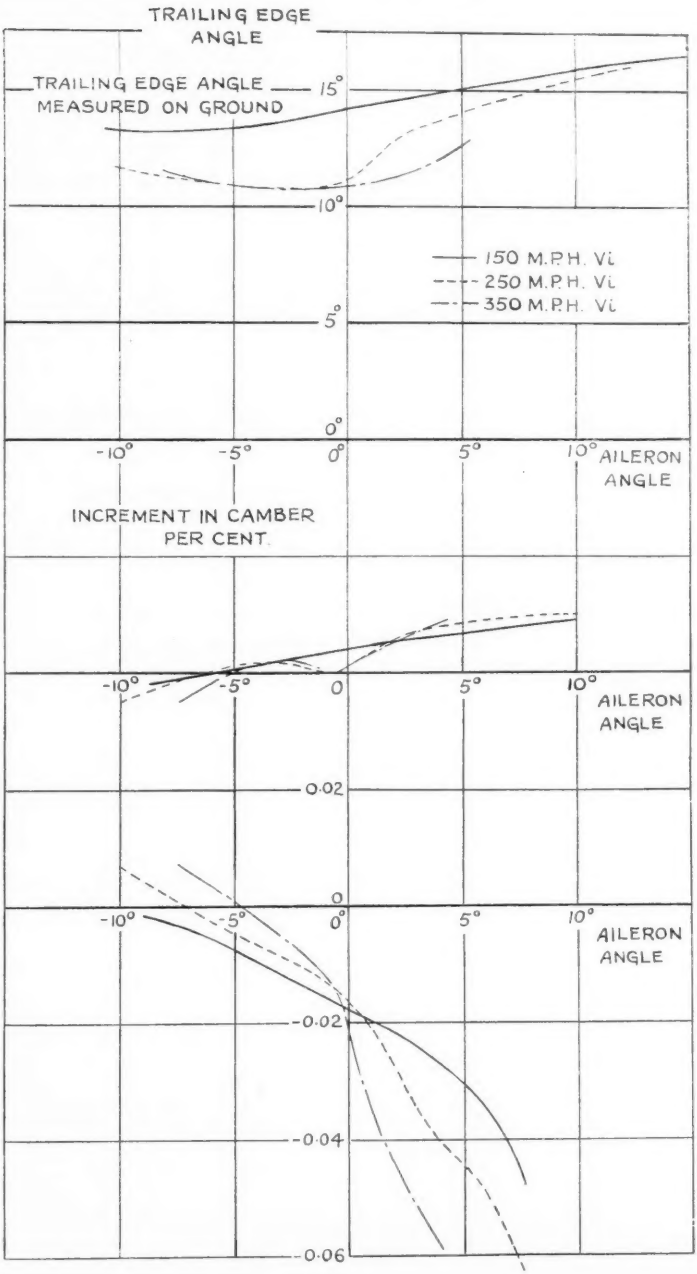


Fig. 2

Comparison of curves corresponding to speeds of 150, 250 and 350 m.p.h. V_i.
Fabric aileron—hinge holes sealed.

feeding back to the stick a proportion of the control hinge moment, or by some independent mechanism. Admittedly many difficulties come in the train of power operation—the need for extreme reliability, the necessity for duplication to safeguard against power failure, etc.; these are formidable matters. But the problem is essentially one of clever mechanical engineering.

It must be confessed that the aerodynamician views such a solution with distaste; it seems an admission of failure. Fortunately an alternative presents itself in the spring tab. It may legitimately be claimed that the spring tab postpones the need for power operation up to sizes of aircraft well above those now in common use, excluding aircraft which may have to operate at high subsonic or supersonic speeds. Since, in addition to coping with "repeatability" troubles, the spring tab possesses a number of further aerodynamic virtues, a section may well be devoted to an outline of the characteristics of this type of balance.

2·83. *The Spring Tab*

A spring tab layout is illustrated diagrammatically in Fig. 3a. The pilot's effort is

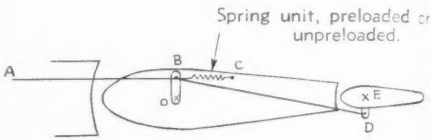


Fig. 3a.

If needed there may be inserted in the rod BD

(i) A trimming jack.

(ii) A subsidiary spring, to magnify the influence on stick force of tab hinge moments about E.

taken in the usual way to the rod AB. Instead, however, of B being fixed to the moving control surface, as in a conventional control, it is attached to one side of a spring unit BC, the other side of which

Diagrammatic sketch of spring tab mechanism.

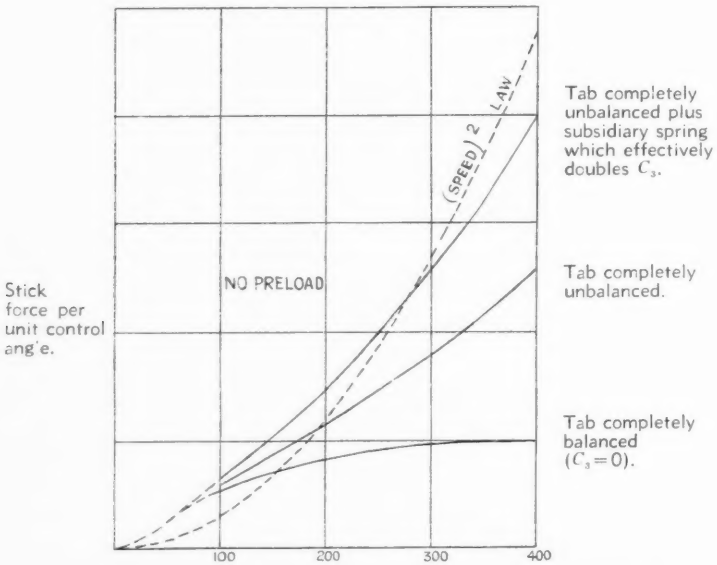


Fig. 3b

Typical characteristic curves for spring tab system.

is earthed to the control surface at C. OB is a lever pivoting freely about the control hinge at O, while BD connects B with the tab crank DE.

Any relative movement between B and C will result in application of the tab. The spring unit BC may be either unpreloaded, in which case compression or extension of BC is directly proportional to the applied load; or it may be preloaded, so that compression or extension only occurs when the applied load exceeds a preset value. It will be seen that the mechanism is so arranged that the tab moves in such a direction as to relieve the pilot's effort.

With a conventional control the stick force per unit control displacement is proportional to the dynamic pressure q, i.e., it varies as (speed)^2. In the case of an unpreloaded spring tab system, however, the stick force per unit control angle varies as

$$q\{1-1/(1+a+b/q)\}$$

where a and b are constants depending on the geometry of the system. The coefficient b is invariably positive, lying usually between $+6$ and $+30$; a depends directly on the degree of balance of the tab about the tab hinge. With a completely balanced tab, a is zero, and the type of characteristic curve obtained is as indicated by the lower curve of Fig. 3b. If the tab is completely unbalanced, a typical value for a is $+0.1$, giving the middle curve of Fig. 3b. By inserting a subsidiary spring in the final tab link, the effect of tab hinge moments can be magnified; the top curve of Fig. 3b indicates the sort of thing that can be done by this means. A very wide variety of characteristics are thus at our disposal.

We are here mainly concerned, however, with the bearing of the spring tab on "repeatability." A spring tab scheme may be thought of crudely as a geared tab layout in which tab gearing is progressively and automatically increased with increase of airspeed. When the pilot applies his control, there is thus at any airspeed a certain gearing between the tab movement and the control surface movement. Now this gearing depends on the balance characteristic of the control surface with tabs locked, which we will call Kb_2 in the usual way. If this basic heaviness is increased, owing to the manufacturing errors and distortions already discussed, tab gearing is automatically increased, thus tending to compensate the increased basic heaviness. Similarly, should the basic heaviness be decreased, tab gearing is automatically decreased.

This effect is illustrated in Fig. 4. Suppose that in the case of a single-engined fighter we are designing for a stick force of 30 lb. for $\pm$ 20° aileron at 400 m.p.h. V_1. With conventional balance this will demand an effective Kb_2 of about -0.02. An alteration of ΔKb_2 of ± 0.05, which we have already suggested must be catered for, will give a ΔP of $\pm$ 71 lb. operating on the design value P of 30 lb. In Fig. 4 the corresponding values of ΔP with a spring tab system are plotted against basic Kb_2, tabs locked, for various values of preload P_0. With an unpreloaded spring tab scheme it can be shown that $\Delta P/P$ is equivalent to $\Delta_\alpha b_2/Kb_2$ where Kb_2 is the tabs locked balance factor. The curves of Fig. 4 show the striking reduction in ΔP which accompanies use of the spring tab. By the time we have reached a Kb_2 of -0.2, ΔP has been reduced from $\pm$ 71 lb. to $\pm$ 7½ lb. even when preload is zero. Experimental confirmation of this effect is given in Fig. 5, illustrating the results of flight tests on a pair of fabric covered Spitfire ailerons fitted experimentally with spring tabs, basic heaviness being increased by the progressive addition of trailing edge cord.

In view of its attractions much work has recently been done on the spring tab layout, both theoretical and in flight. Some of the more important points bearing on this type of balance are summarised below:—

(i) If on any control the design case demands a $-Kb_2$ of less than 0.2

with conventional balance, use of a spring tab is recommended to ensure "repeatability."

(ii) Use of the spring tab enables the designer to control the distribution of effective balance with speed with far

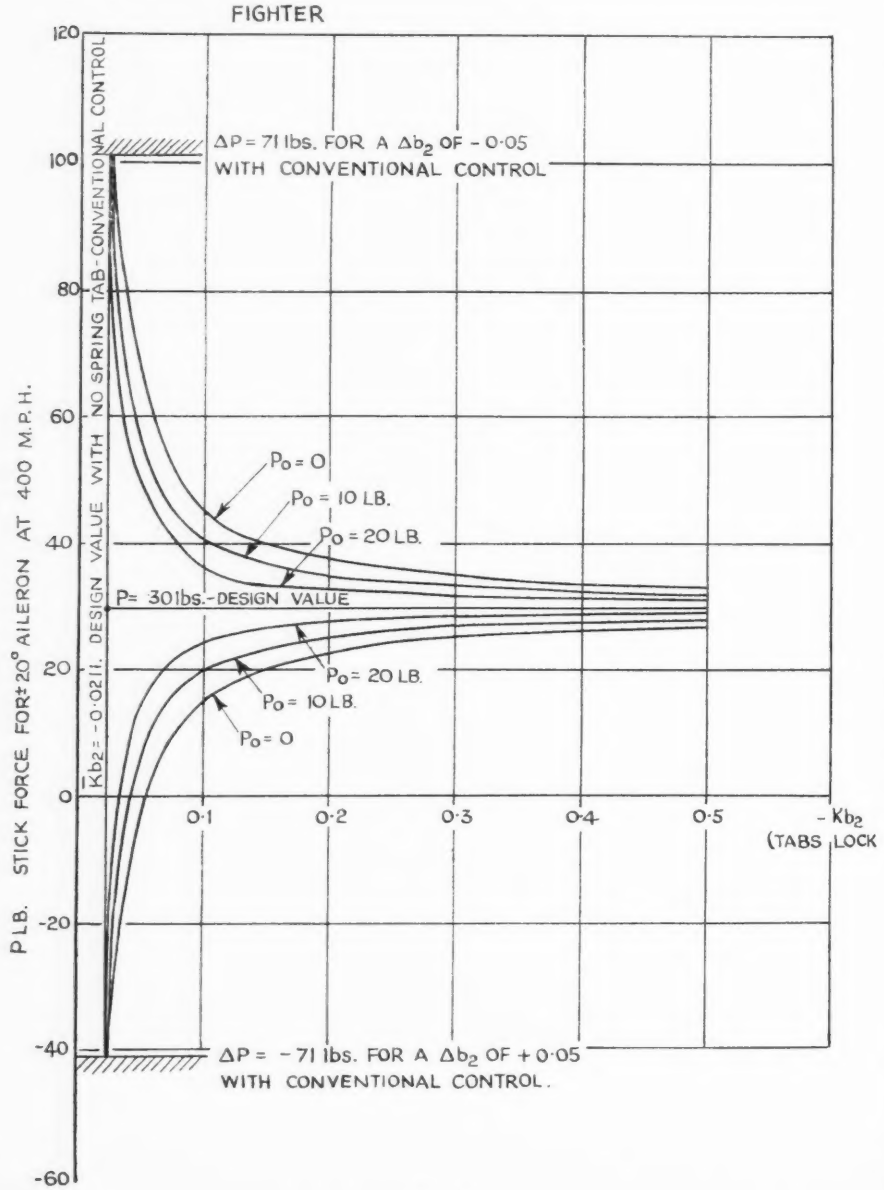


Fig. 4

Influence of basic Kb_2, tabs locked, and preload on increment of stick force due to a variation of ± 0.05 in Kb_2.

greater precision than is possible with conventional balancing methods.

(iii) For all three controls, with spring tab balance:—

(*a*) Tabs locked Kb_2 should lie between -0.2 and -0.3, i.e., some initial balance by set-back hinge or other means is desirable.

(*b*) Tab power b_3 should also lie between -0.2 and -0.3.

(*c*) A follow-up ratio (tab movement/control movement stick fixed) of between 3 and 4 is usual.

(*d*) There is little case for preload.

(*e*) A separate tab is recommended for trimming unless preload is high.

(*f*) Tab and control surface must be mass-balanced, the position of the tab mass balance being bounded by certain limitations as indicated in an appropriate requirement, to safeguard against flutter.

2.9. *Balance Characteristics and Other Points*

The broad subject of balancing methods will be dealt with in Part II. It may, however, be useful here to sketch briefly the way in which differing nose shapes tend to influence the aerodynamic balance.

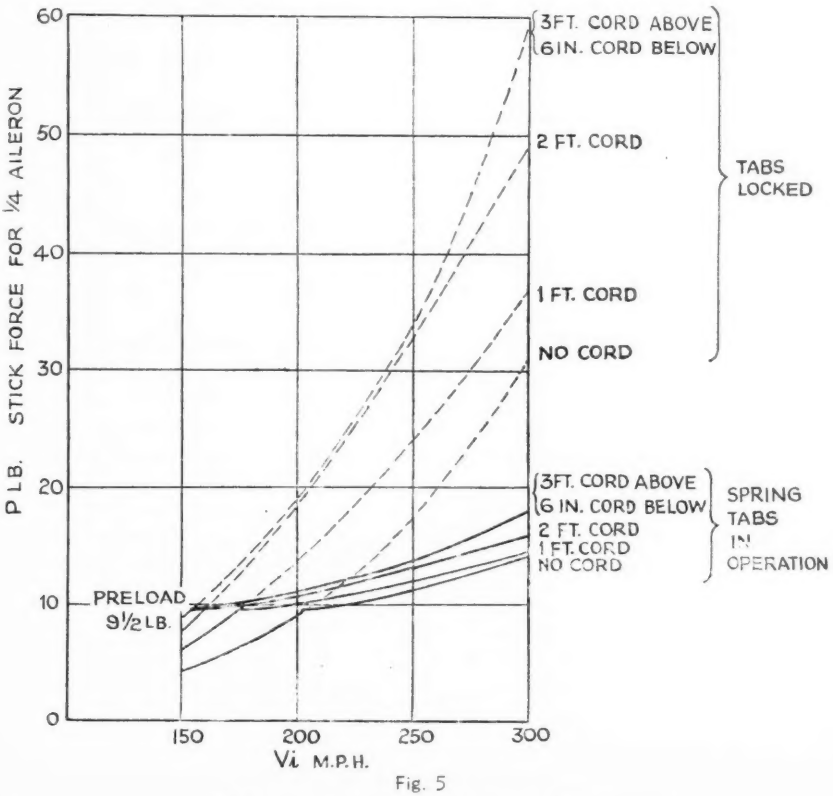


Fig. 5

Flight tests of experimental Spitfire ailerons.
Illustrating comparative insensitivity of spring tabs to variation in Kb_2.

Let us take a symmetrical N.A.C.A. 0009 aerofoil, trailing edge angle 11.6°, having a control whose chord aft of hinge is 30 per cent. of the control chord, a value typical for elevators and rudders. The hinge is assumed on centre line, and for simplicity we will only consider the two-dimensional case.

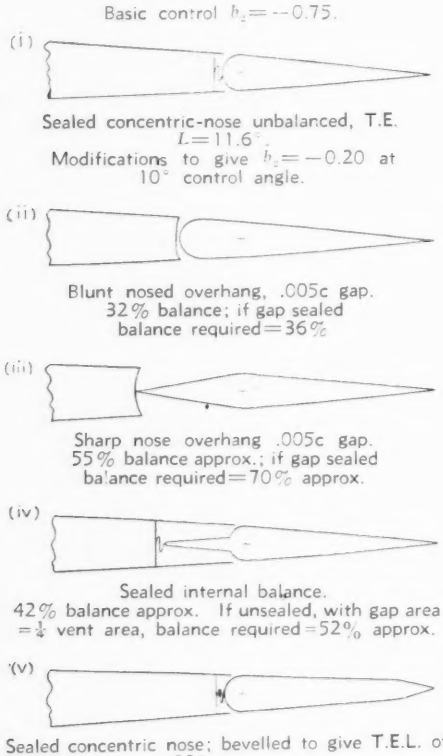

Basic control $b_2 = -0.75$.
(i)
Sealed concentric-nose unbalanced, T.E. $L = 11.6°$
Modifications to give $b_2 = -0.20$ at 10° control angle.
(ii)
Blunt nosed overhang, .005c gap.
32% balance; if gap sealed balance required = 36%
(iii)
Sharp nose overhang .005c gap.
55% balance approx.; if gap sealed balance required = 70% approx.
(iv)
Sealed internal balance.
42% balance approx. If unsealed, with gap area = ¼ vent area, balance required = 52% approx.
(v)
Sealed concentric nose; bevelled to give T.E.L. of 33° approx.
30%c control on N.A.C.A. .0009—two dimensional methods of obtaining a b_2 of −0.2.

Fig. 6

If the nose is made a circle round the hinge and the gap at the nose is sealed, we obtain a value of -0.75 for b_2 at a control angle of 10°. Suppose we put on noses of various shapes in order to reduce this b_2 at 10° to -0.20. In Fig. 6 are drawn to scale the various ways in which such a result can be achieved.

(i) The first sketch indicates the unbalanced control.

(ii) If the nose is blunt and unsealed, 32 per cent. balance is needed, rising to 36 per cent. on sealing the nose.

(iii) If the nose is sharp and unsealed, 55 per cent. balance is required; this would rise to roughly 70 per cent. on sealing the gap.

(iv) Upon adding shrouds and sealing the nose, producing the well-known "internally sealed balance" indicated in the fourth sketch, 42 per cent. balance would be needed. A nose gap equal to ¼ the shroud gap would demand an increase of balance area to 52 per cent.

(v) Lastly, by bevelling the trailing edge to give a trailing edge angle of 33°, we could obtain our b_2 of -0.2 without any nose balance. This should be merely regarded as of academic interest—such a method of balance is undesirable for a variety of reasons.

The general trends are clear. On unshrouded controls blunting the nose aerodynamically lightens the control, while sharpening the nose makes it heavier. In both cases sealing the nose gap makes the control heavier. With a shrouded internally sealed and balanced control more balance area is needed than with an unsealed blunt nosed control, but less compared with an unsealed sharp nosed control; in this case *unsealing* the nose makes it heavier.

While discussing sealing, useful rough figures to carry in one's head for unshrouded controls are that if the nose gap is less than ¼ per cent. of the local aerofoil chord, the control is effectively sealed, from the viewpoint of lift. If the gap is greater than ½ per cent. of the aerofoil chord, the control is effectively fully unsealed.

One other point may be stressed here. The tunnel work to be discussed in Part II

indicates the vital importance of trailing edge angle on hinge moment characteristics. One of the more important practical conclusions to be drawn from this work is that controls with large trailing edge angles have hinge moments that are very sensitive to the wing boundary layer condition, i.e., to transition point position, etc.; departure from linearity of the hinge moment—control angle curve also increases as trailing edge angle goes up. Hence it is a good general rule never to give a control a trailing edge angle greater than 16°, and preferably to give it an angle somewhat less. If this point is borne in mind the chances of producing a good control without lengthy development are greatly increased.

3. *The Individual Controls*

3.1. *Ailerons*

3.11. *Present Practice*

In order to get a rough idea of how designers of military aircraft proportion their ailerons, it is instructive to select about fifteen well-known and modern service types for examination. Three of the more important geometrical parameters are (i) aileron area aft hinge/gross wing area, (ii) aileron percentage balance (area ahead/area aft hinge), and (iii) mean stick or wheel gearing (total control angular range divided by total movement of stick top or wheel rim). In Fig. 7 these have been plotted against gross wing area. Among the aeroplanes selected are:—

Beaufighter (503); Dornier 217 (610); Fortress II (1277); F.W.190 (203); Halifax II (1250); Havoc II (465); Ju.88 (583); Lancaster I (1300); Liberator II (1048); Martlet (260); Me.109F (173); Mosquito (450); Mustang I (236); Spitfire V (242); Stirling I (1460), and Typhoon I (279).

The gross wing area in sq. ft. has been given in brackets after each machine, in order to render the symbols of Fig. 7 identifiable.

It will be agreed that these form a fairly representative cross-section of well tried and highly developed modern types. They fall naturally into three well defined classes: (i) Single-engined fighters, wing area about 250 sq. ft.; (ii) medium sized twins, fighters and bombers, wing area about 500 sq. ft.; and (iii) heavy bombers, wing area roughly 1,250 sq. ft.

The general tendencies are clear. As size goes up there is a slight fall off in relative aileron size, a noticeable increase in percentage balance, and a marked reduction in stick gearing. The latter two trends are what would be expected. The first, a falling off of relative aileron area, is at first sight a little surprising in view of the inevitable reduction in rate of roll with size for a given aileron area, and probably reflects the difficulty of balancing large controls on large aircraft.

Average values from Fig. 7 are given in Table II.

With regard to type of balance, with three exceptions the ailerons of all the aeroplanes listed have some form or other of Frise balance; the variety of nose shapes is considerable, ranging from very sharp to very blunt. Two, Mosquito and Ju.88, have slotted ailerons, while the Mustang ailerons are unbalanced apart from geared tabs.

Maximum aileron angles are usually

TABLE II

CURRENT AILERON PRACTICE

Type.	Gross wing area, sq. ft.	$\frac{\text{Aileron area}}{\text{Wing area}}$	Aileron percentage balance.	Stick or wheel gearing. Deg./inch.
Single-engined fighter	250	0·060	28	2·3
Medium bomber	500	0·058	30	1·8
Heavy bomber	1250	0·052	35	1·2

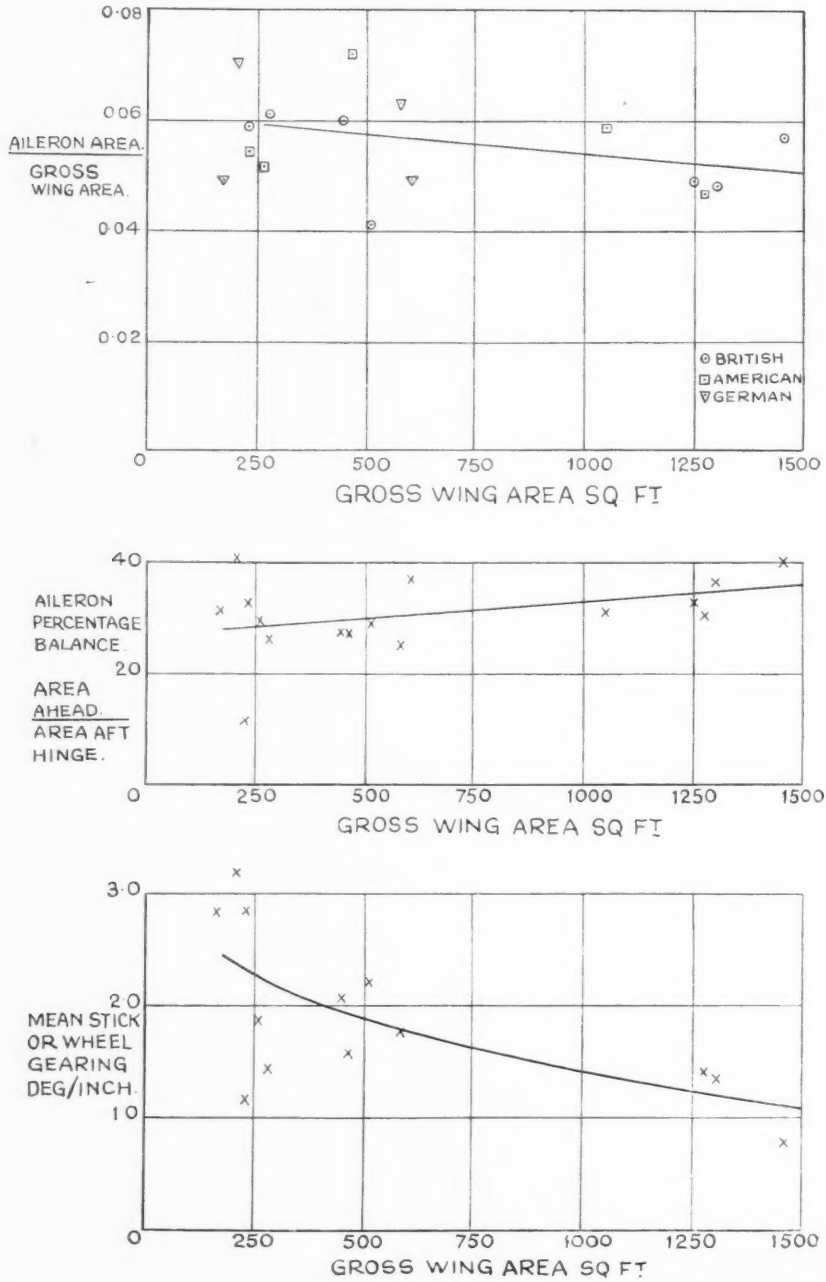


Fig. 7

Military aeroplanes—present practice in aileron design.

between 15° and 20° down, and from 20° to 25° up. Two marked exceptions are the Mustang I, with ± 10°; and the Fortress II, with ± 12°.

3.12. *Aileron Power*

The size of the ailerons is dictated, not by the requirements of high speed manœuvrability, but from considerations of adequacy of control at low speed—primarily from the viewpoint of good aileron control during the approach and landing in bumpy conditions. Experience suggests that if aileron area aft hinge/wing area exceeds 0.05 and the ailerons are worked through roughly ± 20°, aileron power at low airspeeds should be adequate for the classes of aeroplane under consideration. An exception must, however, be made for certain specialised classes—such as carrier-borne aircraft—in which abnormally good lateral control on the approach is desirable.

From consideration of space for flaps, etc., aileron span/wing span cannot normally exceed 0.45, and usually runs between 0.35 and 0.45. From the balancing viewpoint it is attractive to keep the aileron span up and the aileron chord down, having decided on the aileron power required. Short span wide chord ailerons, sometimes considered when a very large flap is needed to give very high lift, are extremely difficult to develop into a nice control compared with ailerons of more normal proportions. Thus in general it is wise when proportioning the ailerons to ensure that (i) aileron area/wing area is greater than 0.05, and (ii) aileron span/wing span is not less than 0.35. Elaborate technical arguments can be given for the optimum relation between aileron span and aileron area, but the conclusions depend so much on the initial assumptions made and on the interpretation of the results that the final answers are no more reliable than the figures from experience quoted above.

With regard to differential, it is customary to use a little, of the order of 18° down aileron angle combined with 25° up. Differential is used partly with the idea of reducing the adverse aileron yawing moment, but a number of successful aileron installations have flown with no differential, maximum angles being about ± 20°.

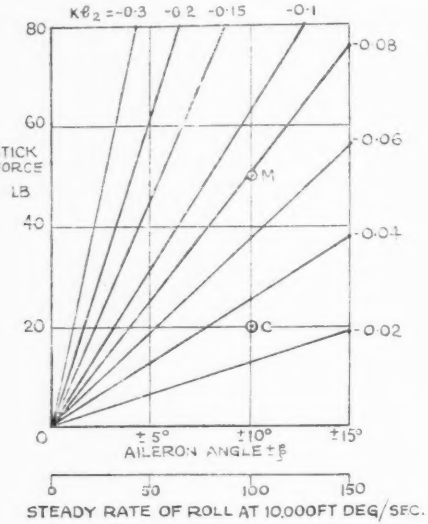
On modern machines the level of weathercock stability is higher than in the past and as a result adverse aileron yawing moment has ceased to be a serious problem. A note of caution must be sounded here, however. As more powerful engines are being installed in single-engined fighters, airscrew size is increasing in order to absorb the extra power, and with this trend comes a marked increase in the destabilising "fin effect" of the airscrew on both weathercock and longitudinal stability. As a result high performance fighters with conventional engines will tend to have less weathercock stability and more attention may have to be paid to adverse aileron yaw.

If adequate aileron power is provided at low airspeeds, there should be more than enough power available for the extremely important military case of manœuvring in a high speed dive, since for a given aileron angle rate of roll increases linearly with true airspeed apart from the falling off at high airspeeds arising from the wing twist which occurs on application of the aileron. This only assumes disastrous proportions if the wing aileron reversal speed (the speed at which wing twist just nullifies the applied aileron) is unduly low; on fighters, provided the reversal speed exceeds 700 m.p.h., ample aileron power should be available at 450 m.p.h. with ailerons of normal proportions. The problem is to utilise this available power by making the ailerons light enough in the dive for the pilots to be able to apply a reasonable aileron angle; which brings us to the all important topic of balance.

3.13. *Aileron Balance*

Let us consider a typical single-engined fighter; wing area 250 sq. ft., and a typical

heavy bomber, wing area 1,250 sq. ft. In Figs. 8a and 8b stick force is plotted against aileron angle for various values of the aileron balance factor Kb_2, the airspeed being taken



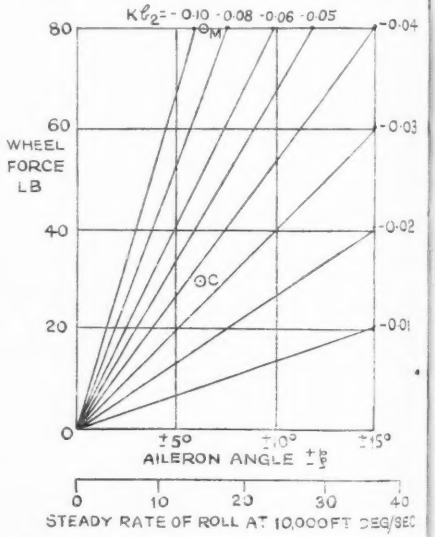
S=250 sq. ft. C_ξ=0.97 ft.
b=38.6 ft. m=2.3 deg./inch.
S_ξ=15 sq. ft. total

Fig. 8a
Fighter. Ailerons at 450 m.p.h. V_i.

as 450 m.p.h. V_i for the fighter, and 300 m.p.h. V_i for the bomber—representative conditions for a high speed dive in which vigorous evasive action may be needed. Values assumed for the relevant geometrical parameters—aileron size, stick gearing, etc., will be found on the figures, while the steady rates of roll appropriate to each aileron angle are indicated on subsidiary scales, height being assumed to be 10,000 ft.

Dealing first with the fighter of Fig. 8a, let us assume that the pilot would like to be able to generate rate of roll of 100 deg./sec. He wants to achieve such a high rate of roll, not of course in order to roll steadily round and round, but in order to get to about 80° bank as quickly as possible preparatory to putting on "g" and turning off sideways to avoid someone who is threatening to shoot him from the rear. This rate of roll demands ±10° of aileron. Reverting to our typical pilot of Table 1, we see that he does not like to put more than 20 lb. on the stick, and we have decided that it would be unfair to ask him for more than 50 lb. Taken in conjunction with an aileron angle of ± 10°, these forces give us the points C (convenient) and M (maximum) of Fig. 8a. To achieve even M, it can be seen, demands a value for the aileron balance factor Kb_2 of −0.08; while to get down to C we want Kb_2 of about −0.03.

As already discussed in para. 2.81, it is not practical politics to work to a $-Kb_2$ of less than 0.05 with conventional balancing methods; and whatever we choose, we must expect a variation ΔKb_2 of ±0.05 from aileron to aileron—owing to manufacturing



S=1,250 sq. ft. C_ξ=1.77 ft.
b=106 ft. m=1.2 deg./inch.
S_ξ=75 sq. ft. total

Fig. 8b
Heavy bomber. Ailerons at 300 m.p.h. V_i.

errors and distortion—unless quite exceptional care is taken in manufacture. Hence with conventional aerodynamic balance—Frise, geared tab, and the like—it is not

practicable to give the pilot C. We can give him M at the expense of a probable variation in aileron heaviness of more than ± 60 per cent. (± 0.05 ΔKb_2 on a basic Kb_2 of -0.08) from machine to machine, with consequent delay in carefully selecting individual ailerons by trial and error during production test flights. In para. 2.82 it was pointed out that there were two ways round the difficulty. We can consistently give the pilot not M but C by adopting (i) spring tab balance, which irons out errors in basic heaviness, thus rendering the ΔKb_2 of ± 0.05 innocuous. or (ii) power operation, which burkes the problem by brute force. For this particular application the authors favour the spring tab, on grounds of simplicity and reliability.

Similar arguments hold for the heavy bomber, as indicated in Fig. 8b. Here the pilot has a wheel, which alters the " convenient " and " maximum " forces to 30 lb. and 80 lb. respectively. In this case we will demand a rate of roll of 15 degrees per second; this will allow reasonably rapid evasive action to be taken in relation to the size of the aircraft. It will be seen that the points M and C correspond to values of Kb_2 of about -0.10 and -0.035 respectively, not very different from those of the fighter. The same problems thus arise, and the logical solutions—spring tabs or power operation—present themselves again; on an aircraft of this size, spring tabs would again seem the preferable solution.

3.14. *Sundry Points*

A few disconnected jottings on various other aspects of aileron design are included below:—

(i) Provided the ailerons are self-centring, many modern pilots demand very little " feel " at low airspeeds on the approach, appreciating very light stick forces for full aileron.

(ii) Current methods of doctoring Frise ailerons include rigging both ailerons down if too light, and rigging both up if too heavy—this must be indulged in with caution since overbalance easily results. Adjusting the up and down position of the hinge in relation to the wing, by trial and error, is also practised; unless undertaken by highly trained personnel, such adjustment is very undesirable.

(iii) Unsatisfactory distribution of balance with airspeed, arising from an unpredictable variation of Kb_2 with speed, is more likely if the aileron trailing edge angle is large: as already mentioned in para. 2.9, it is wise to keep the trailing edge angle below 16°. The spring tab affords by far the most convenient method of controlling the distribution of balance with speed.

(iv) Although possibly not a design case, adequacy of aileron control in recovering from the consequences of one engine cutting on a multi-engined machine is an important point which must be checked in flight.

(v) From their very nature, ailerons are rarely very effective near the stall. Pilots have got used to regarding the rudder as the primary lateral control in this region.

(vi) Automatic leading edge slots are liable to cause a marked aileron " snatch " just as they open. This can be very disconcerting under " g " at high airspeeds.

(vii) Rolling moment of inertia plays less part in the crispness of a fighter's response to aileron than is popularly supposed. On a given aeroplane a variation of ± 25 per cent. in the rolling moment of inertia will be barely perceptible to the pilot in terms of quickness in starting and stopping a roll at high airspeeds.

(viii) From the strength aspect on military aircraft, ailerons are in a different category from elevators and rudders. Large aileron angles are an operational necessity at high airspeeds. There is thus no question of restricting the amount of aileron a pilot can apply—the wing and aileron structure must be strong enough to take these large angles. Normally this only means local stiffening, the main wing structure usually being made sufficiently strong in torsion, quite apart from the aileron case, to meet stiffness requirements.

3.2. *Tailplane and Elevator*

3.21. *Present Practice*

Taking the same list of aeroplanes as that given in para. 3.11, some of the more important geometrical characteristics relating to tailplane and elevator design are plotted against wing area in Fig. 9; the characteristics illustrated are tail volume coefficient, elevator area/gross tail area, elevator percentage balance and stick gearing.

Dealing with these in turn, it will be seen that on the medium and heavy types our American colleagues favour bigger tails than ourselves. On fighters, however, the unanimity with which American, British and German designers choose a tail volume coefficient of about 0.45 is very strking. With regard to the ratio elevator area/gross tail area, this falls steadily from 0.34 for fighters to 0.27 for the heavies; the scatter of the points about the mean line is remarkably small. Elevator percentage balance rises rapidly with size, while stick gearing falls appreciably.

Average values from Fig. 9 are given in Table III.

The most popular method of balance is set-back hinge, this being used on nine of the types considered, combined in some cases with a geared tab. Five other of those aeroplanes on our list have some form of horn balance on the elevator, again combined in certain cases with a geared tab. One aeroplane, the Mustang, has neither forward balance nor tab balance.

Maximum up elevator angle is usually round about 25°; there is one marked exception, the Junkers 88, which has nearly 40° of up elevator. Maximum down elevator angle is normally in the region of 20°.

Three of the German aeroplanes considered —Me.109F, FW.190 and Ju.88—have tailplanes whose incidence can be adjusted in flight. This is used for trimming on the Me.109F and FW.190, but the Ju.88 elevator is fitted with a trimmer tab, tail incidence only being changed on lowering the flaps. None of the other machines considered in Fig. 9 have adjustable tailplanes—in each case trimming being effected by trim tabs on the elevator. The relative size of the trimmer tabs varies within wide limits from type to type, but maximum trim tab angles are with few exceptions less than ± 15°.

TABLE III

CURRENT TAILPLANE AND ELEVATOR PRACTICE

Type.	Gross wing area, sq. ft.	Tail volume coeff. $\bar{V}$.	Elevator area / Gross tail area	Elevator percentage balance	Stick gearing Deg./inch.
Single-engine fighter	250	0.44	0.34	11	3.7
Medium bomber	500	0.60	0.32	18	3.4
Heavy bomber	1250	0.60	0.27	41	2.4

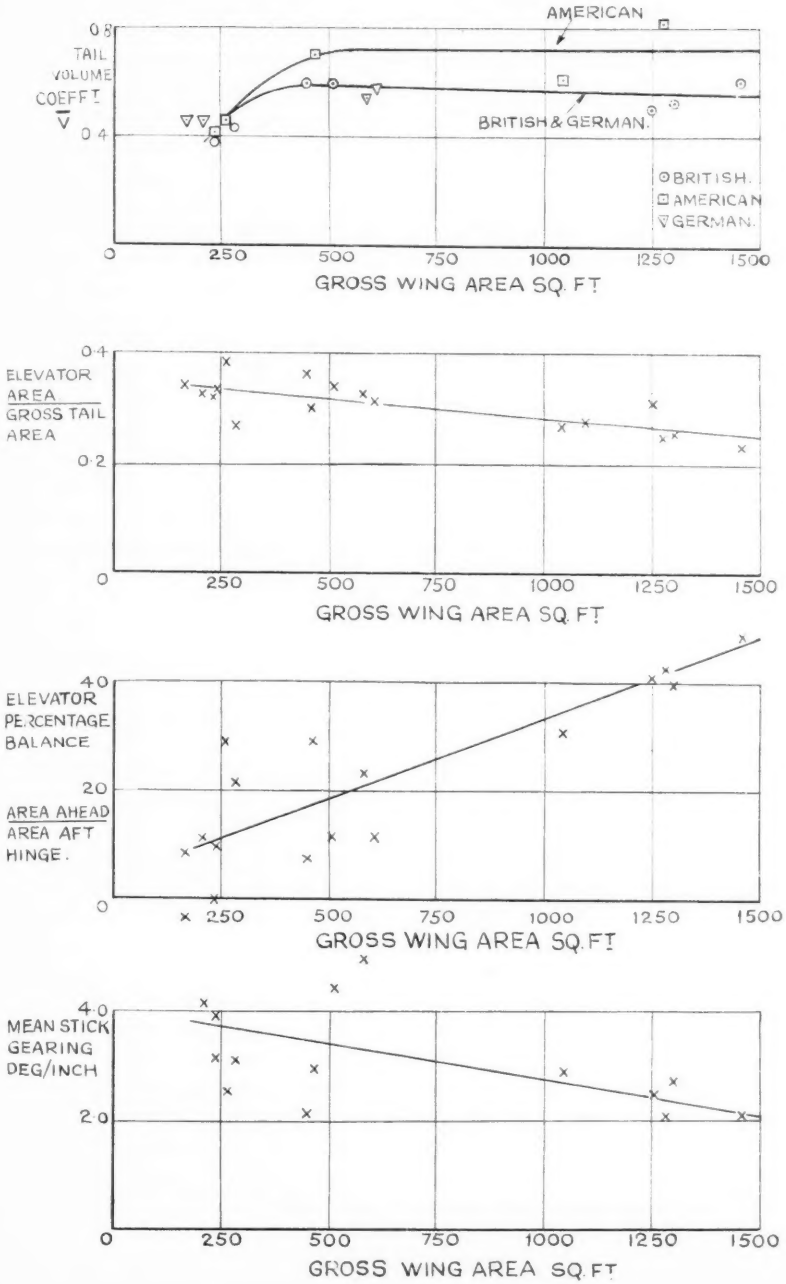


Fig. 9

Military aeroplanes—present practice in tailplane and elevator design.

3.22. *Tail Size—Longitudinal Stability*

We cannot divorce the balance and lift characteristics of the elevator from the longitudinal stability of the aeroplane as a whole, since as indicated in para. 2.6 these features are intimately connected. Let us first confine our attention to a rigid aeroplane, i.e., an aeroplane whose structure does not distort at high airspeeds. It is well-known that as the centre of gravity moves aft the aeroplane gets progressively less stable. In this connection there are four useful conceptions which help greatly in clarifying any discussion of longitudinal stability. The first two of these, the " neutral points," are old and well-known; the last two, the " manœuvre points " have been popularised in recent years by the theoretical work of Mr. S. B. Gates and Miss H. M. Lyon.

(i) The " stick fixed neutral point " is that centre of gravity position at which there is no change of elevator angle to trim with speed. When the centre of gravity is not on the neutral point, its distance ahead of the neutral point, in terms of the mean chord, is called the " stick fixed static margin."

(ii) The " stick free neutral point " is that centre of gravity position at which, having trimmed the elevator at one particular speed, no stick force is needed to hold the aeroplane at a new speed without retrimming. At any other centre of gravity position, its distance ahead of this neutral point is called the " stick free static margin."

The stick fixed neutral point is independent of the balance characteristics of the elevator, unless the balance arrangement demands a gap at the control nose which may reduce the slope of the tail lift curve. The difference between the stick fixed and stick free neutral points is determined largely by the ratio b_1/b_2, as noted in para. 2.6.

(iii) The " stick fixed manœuvre point " is that centre of gravity position at which the stick movement needed to hold a steady normal " g " at constant airspeed is zero. The corresponding margin is called the " stick fixed manœuvre margin."

(iv) The " stick free manœuvre point " is that centre of gravity position at which the stick force per " g " is zero; the margin is termed the " stick free manœuvre margin."

Since stick forces are far more important than stick movements to a pilot, the stick free margins play a larger part in the " feel " of the elevator than their stick fixed opposite numbers. In general the manœuvre point is aft of the corresponding neutral point, i.e., when the centre of gravity is on the stick free neutral point, there is still a positive stick force per " g."

Ideally, if the aeroplane is rigid and the aerodynamic " constants " really are constant, the stick fixed and free neutral points stay put over the whole speed range until the stall is approached; the trim curves are linear. Excluding very high speeds, this condition is often true in real life on the glide. At full throttle, however, slipstream commonly exerts a destabilising effect which becomes accentuated at low airspeeds; as speed is decreased, the neutral points move forward.

When a designer has decided roughly on the shape of the wings and body, two courses are open to him if he wants to aim for a certain stick fixed static margin. He can either put the centre of gravity forward, and fit a small tailplane; or he can arrange his loads to give a further aft centre of gravity, and put on a larger tail. In practice, however, on aircraft of conventional layouts, he has not a great deal of control over the centre of gravity position, which normally ranges between 0.25 c. and 0.35 c. Experience suggests that the tail should be large enough to give at least neutral static stability, stick fixed, in cruising flight with the centre of gravity on the aft limit; a possible exception can be made in the case of small fighters, which can tolerate a small adverse stick fixed margin provided the stick free static margin is positive.

A difficulty enters here, however, in that as time goes on the centre of gravity of an aeroplane moves steadily aft, because the most obvious place to put additional equipment is in the fuselage behind the centre of gravity. Hence it is wise to start off with a stick fixed static margin of 0.02—0.04 c. with the C.G. aft, cruising, as an insurance against future rearward C.G. drift. It is obviously economic to design initially for as far forward a centre of gravity as is practicable, to avoid the necessity of excessive tail area, with its accompanying weight and drag.

3.23. *" Stick-free " Stability*

We have already seen that the loss or gain in stability on freeing the stick depends largely on the ratio b_1/b_2. Now, while an aeroplane may be quite acceptable if it is slightly unstable stick fixed, all classes of aeroplanes, large or small, should be considered unacceptable if unstable stick free. From the pilot's point of view stick free instability implies tightening up in turns, self-stalling and reversal of stick force on altering speed—all highly undesirable.

Since designers are constantly faced with rearward C.G. drift on their aeroplanes, and since the pilots only start complaining vigorously when the C.G. arrives in the neighbourhood of the stick free neutral point, methods of shifting this point back by relatively small modifications to the elevator balance are of considerable practical importance.

With normal set-back hinge balances b_1 is normally negative, and there is a loss of stability on freeing the stick—considerably accentuated if b_2 is made very small by use of a geared tab. Aerodynamically there are two main ways of swinging b_1 over from negative to positive, one well-known, the other not so well-known.

(i) Horn balance. Gains in stability on freeing the stick of more than 0.05 c. can easily be obtained by fitting an unshielded horn. Care must be taken in positioning the horn, since if it is in an irregular wake the pilot will get a constant jerking on the stick; this can easily happen on a multi-engined machine if the horns are behind the nacelles.

(ii) Set-back hinge with anti-balance tab. As percentage balance is increased, b_2 first becomes positive, then with still more balance b_1 becomes positive, with blunt or medium nose shapes. The overbalanced b_2 of such a control can be reversed in sign by fitting an anti-balance tab (i.e., a geared tab acting the opposite way from normal, called in America a " leading tab "), leaving b_1 positive, and thus giving a gain in stability on freeing the stick. This is more attractive than the horn, since the balance is not so localised, and so is less susceptible to local irregularities of flow. A number of such installations have been flown with considerable success.

Whatever is done to make b_1 more positive, an important consequence will be that in terms of stick force the change of trim on lowering the flaps will become more nose-up, since the added downwash will tend to make the elevator float upwards if b_1 is positive. This can be a very embarrassing feature if, on an existing type, large horns are added to the elevator to improve stability.

In general it is unwise to attempt a gain in stability of much more than 0.05 c. on freeing the stick. Elevators with a very large positive b_1 have an unpleasant " feel " in bumpy air, as they tend to respond rather too vigorously to the changes in tail incidence which occur in bumps.

Other devices which can be used for increasing the stick free stability are weights and springs. A constant moment, applied by a weight on an arm or by a long spring, tending to move the elevator down, will add to the stick free stability. We will not go into the physical explanation of this here; in our view use of such devices should not be encouraged. They should be regarded as temporary expedients, only to be adopted in emergency, and should never be incorporated

in a design from the outset. A weight moment is unpleasant to the pilot when taxying. A spring can, in certain circumstances, have an unfortunate influence on the dynamic stability.

3.24. *Stick Force per " g "*

In our rigid aeroplane with well behaved " constants," stick force per " g " depends on the stick free manœuvre margin, and is independent of speed. In this respect the elevator is fundamentally different from the aileron; we have no (speed)^2 law to beat. Stick force per " g " is, however, critically dependent on C.G. position, getting less as the C.G. moves aft and disappearing when it reaches the manœuvre point.

Owing to this interaction between C.G. position and manœuvrability, it is impossible to generalise about elevator balance in the way we did on ailerons. It is quite possible to have an aeroplane whose stability characteristics are such that the degree of elevator balance needed is determined, not by consideration of manœuvrability at high speeds, but by the case of applying large angles for reasonable forces when getting down the tail on landing.

Something can, however, be said about desirable values for stick force per " g." On fighters, designers should aim at giving the pilot between 3 and 8 lb./" g "; under no conditions should the stick force per " g " be less than 3 lb., in the interests of safety. It should be noted that with the values quoted above the pilot can easily break the aeroplane, breaking " g " normally being about 10. The occurrence of " black-out," however, provides a natural warning of excessive " g."

Turning to heavy bombers, appropriate figures are more debatable. It is suggested, however, that the stick force per " g " should be such that it requires a pull of about 100 lb. to reach breaking " g." With heavy bombers, breaking " g " is less than black-out " g," so that this particular warning is absent. Nevertheless, 100 lb. is unlikely to be applied inadvertently. Taking breaking " g " as 4, this force means a stick force per " g " of about 35 lb. It is appreciated that many will consider this unduly low. It is suggested here primarily to promote discussion.

3.25. *Distortion Effects at High Airspeeds*

When an aeroplane is diving at high airspeed the aerodynamic forces cause structural distortions — fuselage bending, twisting of the tailplane and elevator, bulging of the control panels, etc.—which are nowadays sufficiently large to have a profound influence on the behaviour of both fighters and bombers in the dive. The theory of such " aeroelastic " effects on longitudinal stability and control has recently been examined by Mr. S. B. Gates and Miss H. M. Lyon. The matter is extremely complicated, and no attempt will be made to go into detail here. A few broad statements on practical aspects may be useful, however. The most obvious consequences to the technician are that trim curves no longer obey the rules at high airspeeds—neutral points tend to go to infinity, etc. On modern fighters the stick force needed to hold an aeroplane in the dive without retrimming is largely determined by aeroelastic behaviour. An important theoretical conclusion which has in numerous cases been borne out in practice is that if the stick force to hold in the dive is excessive because of such effects, it can be reduced by increasing the fixed tailplane incidence; this leaves stick force per " g " unaltered. Determination of the neutral points is valueless in the dive if distortion effects are large. The conception of the stick free manœuvre point, however, still retains its utility. The most satisfactory way of determining whether an aeroplane is acceptable in the dive is by a direct assessment of the qualities important to the pilot, namely:—

(i) Stick force to hold in the dive without retrimming.
(ii) " g " on releasing this force.
(iii) Stick force per " g."

3.26. *Other Points*

(i) The elevator power required is governed largely by the need for getting the tail down on landing with C.G. forward. When setting out a new design the best guide to what will be needed is past experience, since ground effect renders a detailed analysis of the problem difficult.

(ii) Bearing in mind our average pilot of para. 2.2, it should be the designer's aim to keep the changes of trim in terms of stick force on lowering flaps, opening up the engines for a baulked landing, etc., within the limits ± 30 lb., so that a pilot can comfortably hold them with one hand while adjusting his throttles and trimmers with the other.

(iii) Flight experience of elevator behaviour at very high Mach numbers is limited. So far no deleterious effects of horn balance have been observed, while tab effectiveness appears to be retained after a shock stall of the main planes.

(iv) Owing to propeller destabilising " fin effect " the tail volumes indicated for fighters in Fig. 9 may be expected to rise in future, as powers and propeller sizes go up.

3.3. *Fin and Rudder*

3.31. *Present Practice*

Keeping to the same list of aeroplanes as that given in 3.11, geometrical characteristics of the fins and rudders are plotted against gross wing area in Fig. 10. Apart from fighters, the Americans again favour rather larger fins than ourselves. The ratio rudder area/total fin and rudder area falls from 0.5 for fighters to 0.25 for the heavy bombers, while percentage balance rises rapidly from about 10 per cent. to over 30 per cent. Pedal gearing falls with increasing size. Average values from Fig. 10 are tabulated below.

The method of balance is fairly evenly divided between set-back hinge and horn, combined in many cases with a geared tab. Two of the types, Mosquito and Ju.88, are fitted with spring tabs. Maximum rudder angles are usually round about ± 25°, with the exception of two of the German machines; the Me. 109F has maximum angles of ±34°, and the Ju. 88 ±41°.

All the aircraft considered have trim tabs on the rudder adjustable in flight, with the exception of the Me.109F and the FW.190; on both these aircraft no means of trimming the rudder in the air is provided. Maximum tab angles vary from ± 6° to ± 25°, the normal figure being in the region of ± 15°.

3.32. *Design Cases*

Provided an aeroplane has a reasonable degree of weathercock stability, the rudder is the least used of the controls for normal flying, and is regarded by many as a glorified trimmer. By reasonable weathercock stability is meant a value for the non-dimensional coefficient n_v of at least 0.06 on medium and large aircraft. Destabilising

TABLE IV

CURRENT FIN AND RUDDER PRACTICE

Type.	Gross wing area, sq. ft.	Fin and rudder vol. coeff.*	Rudder area / Nett fin and rudder area	Rudder percentage balance.	Pedal gearing, deg./inch.
Single-engined fighter ...	250	0.10	0.5	8	8.0
Medium bomber	500	0.10	0.45	14	7.5
Heavy bomber	1250	0.10	0.27	33	5.5

* Based on *gross* fin area, i.e., including body beneath fin.

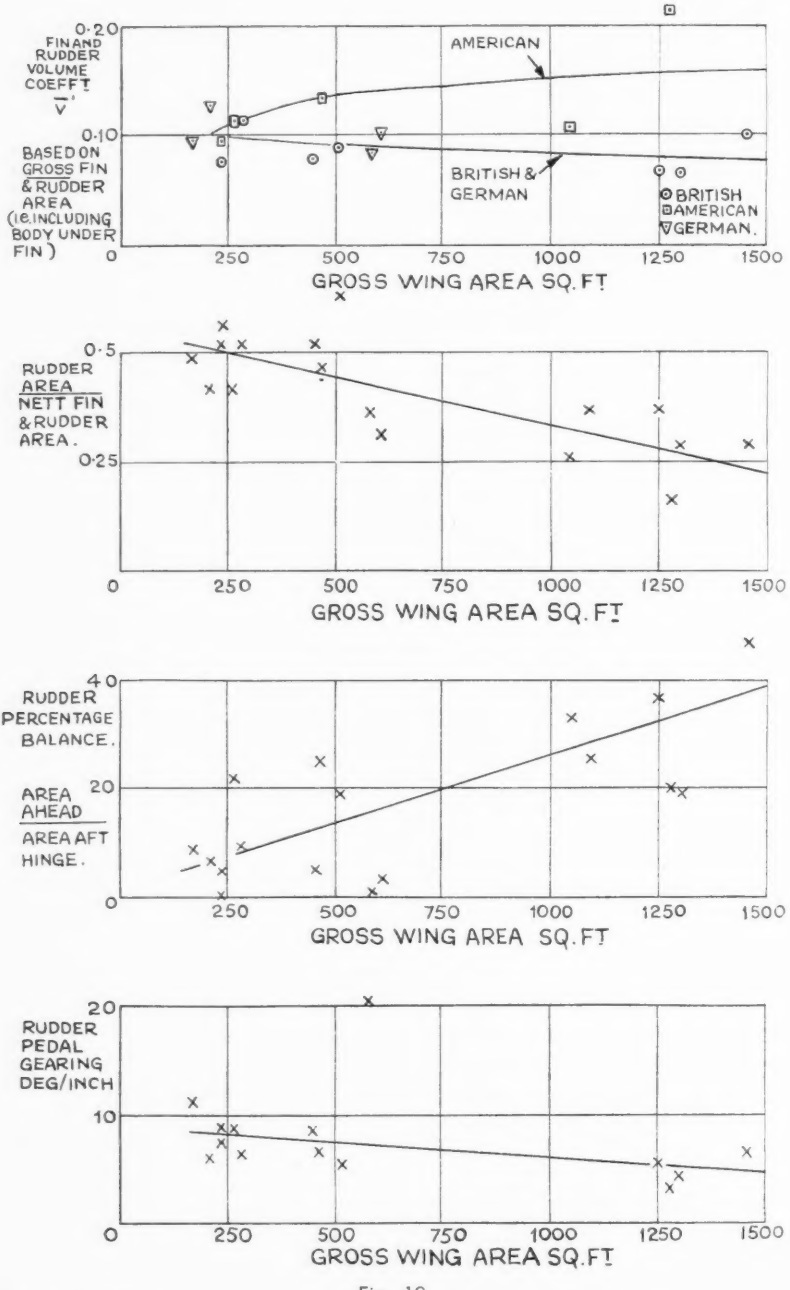


Fig. 10

Military aeroplanes—present practice in fin and rudder design.

airscrew "fin effect" is rapidly becoming so pronounced on high powered fighters that it is difficult to achieve a value of n_v greater than 0.06 on such aircraft; it is suggested, however, that n_v should not be allowed to fall below 0.03, rudder fixed.

On single-engined aircraft with conventional engines and no contraprops, rudder power is determined largely from considerations of:—

(i) Ability to prevent swing during take-off.

(ii) Ability to prevent sideslip during the initial climb at full throttle.

On such aircraft rudder balance is settled, often by trial and error, by the problem of keeping the leg loads needed to cope with changes of directional trim with speed and throttle setting within reasonable limits. Turning to our typical pilot of para. 2.2, we see that our aim should be to keep such loads within ± 60 lb. This has become a major design problem on small aircraft with very powerful engines. Owing to the complicated nature of the slipstream distribution over the fin it is very difficult to generalise about the best ways of tackling the problem. Two points may be of value:—

(i) Assuming the change of trim on opening or closing the throttle arises largely from a change in the mean sidewash at the fin, the resultant pilot's effort to prevent sideslip can obviously be modified by altering the b_1 of the rudder. In one or two cases this has been borne out in flight during development work.

(ii) The spring tab has also been used effectively in tackling this problem. The tab itself should be unbalanced to assist in preventing undue lightness at high airspeeds.

The relative positioning of fin and tailplane is often determined from consideration of good anti-spinning qualities. The empirical criteria for rudder shielding, etc., are now well-known, and will not be enlarged upon here.

Turning to multi-engined aircraft, rudder power is determined largely from considerations of holding the aircraft straight when one engine suddenly fails during a full throttle climb at low airspeeds; while rudder balance is dictated by the same condition—again we should ideally keep the pilot's foot load below 60 lb. during any corrective action he has to take.

A large amount of rudder power is usually needed for the above case, and one of the main arts of fin and rudder design on multi-engined machines lies in preventing this available power from becoming an embarrassment to the pilot in normal flying. In particular under no circumstances should it be possible for the pilot to stall the fin by applying excessive angles of sideslip—this will be considered separately later.

Although, as already suggested, the rudder is the least used control during normal manœuvres, fin and rudder design deserves particularly keen attention on medium and large service aircraft. Experience has shown clearly that incorrect use of the rudder, leading to inadvertent sideslip, is one of the more important factors in causing a relatively inexperienced pilot to lose control when flying on instruments in cloud or at night. The most likely fault is failure to correct promptly, with the rudder, sideslip arising from changes of directional trim with speed and with throttle setting. At high speeds such inadvertent skid, when combined with high dihedral and heavy ailerons, can result in a spiral dive with the speed mounting rapidly, from which recovery is difficult unless vigorous action is taken to remove the sideslip, possibly with assistance from the rudder trimmer. To guard against such a possibility it is obviously desirable that:—

(i) Weathercock stability should be reasonably high, to cut down the magnitude of the inadvertent skid; this was one of the reasons behind our

recommended value of at least 0.06 for the n_v of medium and large aircraft.

(ii) Change of directional trim with speed and throttle setting should be as small as possible. This is a difficult technical problem, unless contraprops or opposite handed airscrews are fitted. Its solution, moreover, may not seem so urgent to the designer as it might, since to a highly skilled test pilot flying in the daytime a certain degree of change of trim may appear innocuous, even though it were sufficiently great to worry a less highly trained pilot under more difficult circumstances. In the case of both single- and twin-finned aircraft, particularly twin, the effect of fin and rudder position and size on this feature can be studied during prototype trials. Judicious manipulation of the rudder b_1 and b_2 may result in a marked reduction of these directional trim changes. Thorough development work on this point is well worth while in every case.

3.33. *Fin and Rudder Stall*

An aeroplane is usually unstable directionally to a marked degree with the fin and rudder removed. This unstable body yawing moment is one of the reasons behind the danger of a fin stall. If the angle of sideslip exceeds about 20°, and special precautions have not been taken, the fin and rudder combination may stall. The unstable body moment then takes charge, and causes the aeroplane to yaw rapidly still further; such excessive yaw may be accompanied by a violent rolling tendency, via dihedral, and may well result in complete loss of control.

The dangers of a fin stall are further aggravated by the phenomenon popularly known as "rudder locking." As the fin stall sideslip angle is approached, the rudder hinge moment characteristics usually change abruptly in such a manner as to make the rudder want to go over in the direction for increasing the sideslip. From the pilot's viewpoint this is equivalent to overbalance. Suppose a pilot is applying left rudder in order to sideslip to starboard, pushing with his left foot. The first indication that the fin stall region is being approached is usually a lightening of his leg load, followed by the rudder pedal running away from his foot and going hard over to port. If the airspeed is low enough a light push on the starboard pedal may suffice to get the rudder off before a dangerous manœuvre develops; but it is quite possible for the hinge moments to be so high that the pilot, pushing with all his strength on the starboard pedal, cannot get the rudder off; from his viewpoint the rudder is aerodynamically "locked."

From the foregoing it is obviously desirable so to proportion the fin and rudder that it is either impossible or very unlikely for the pilot to get into this region. In the case of single-finned aeroplanes this is most conveniently done by adding a dorsal extension to the fin. This has the property of greatly increasing the angle of sideslip needed to stall the fin, as indicated in Fig. 11. Such a solution is not open to us on twin-finned layouts. The stalling angle of the fin is increased somewhat by keeping to a fairly low fin and rudder aspect ratio, but we must be prepared for a smaller stalling angle than that obtained with a dorsal central fin—something less than 20° as compared with the 30° or more possible with a dorsal. Our procedure here should be that, having decided what rudder power is needed, enough fin area must be provided to keep the angle of sideslip for full rudder at low airspeeds below that at which the fin stalls, making some allowance for overswing in a dynamic manœuvre.

3.34. *"Rudder-free" Stability*

The same b_1/b_2 arguments for the effect of freeing the control already put forward in para. 2.6 apply, of course, to the fin and

rudder. On small high powered aircraft, when airscrew destabilising effect makes the attainment of a high degree of rudder fixed stability difficult, it is attractive to give the rudder a positive b_1, by use of a horn or other means (e.g., overbalanced control with anti-balance tab), thereby increasing the rudder free stability, and so increasing the pedal loads needed to generate a given angle of sideslip; this may be very desirable at high airspeeds in order to prevent excessively large sideslip angles, dangerous from the structural viewpoint, being developed with undue ease.

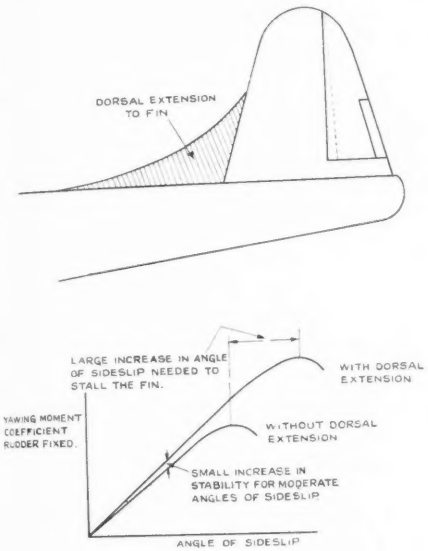

DORSAL EXTENSION TO FIN
LARGE INCREASE IN ANGLE OF SIDESLIP NEEDED TO STALL THE FIN.
WITH DORSAL EXTENSION
YAWING MOMENT COEFFICIENT RUDDER FIXED.
WITHOUT DORSAL EXTENSION
SMALL INCREASE IN STABILITY FOR MODERATE ANGLES OF SIDESLIP
ANGLE OF SIDESLIP

Fig. 11

Diagram illustrating influence of a dorsal fin on weathercock stability.

A word of caution must be put in here. If a positive b_1 is used in conjunction with a very small negative b_2, a combination easily obtained with a horn balanced rudder fitted with a geared tab to reduce b_2, there is a possibility of the aeroplane developing an undamped short period oscillation in which rapid movement of the rudder from side to side plays an essential part—the tail wagging the dog. Such an oscillation is known as "snaking." Once it develops it is usually uncontrollable by the pilot, who must reduce speed until it stops; if speed is increased it gets rapidly more violent and can result in structural failure.

The theory of this is fairly well established. The cure lies in reducing the value of the positive b_1—it can be shown mathematically that making b_1 zero or negative is a fairly complete safeguard against "snaking" provided the rudder is statically mass-balanced. The easiest way of quickly reducing the positive b_1, should this trouble be encountered on a prototype, is by attaching a length of cord at the trailing edge of the rudder on each side, over a portion of the rudder span. Cord about 3/16 inch diameter is commonly used, and the development engineer would start with about a foot of cord on each side and then work up to larger lengths by trial and error until the trouble was cured.

4. *The Very Large Aircraft*

The topic of how to control adequately aeroplanes weighing 250,000 lb. and upwards is rapidly passing from the realm of speculation and becoming one of fairly urgent practical moment. No attempt will be made here to discuss, even in outline, the stability and control problems likely to arise on such very large aircraft; a complete lecture could be written on this theme. We would like, however, to touch briefly on the control balance problem.

We have seen that when aeroplanes are being produced in quantity it is not practicable from "repeatability" considerations to work to a $-Kb_2$ smaller than 0.05 with conventional balancing methods. In the case of very large aircraft, produced possibly in more limited numbers, this figure may come down to say 0.03. Now assume that the relative sizes of the controls of the big aeroplane are not vastly different from those to which we are accustomed. Taking a wing loading of 45 lb./sq. ft. and our aileron

design case as $\pm$ 20° aileron at 150 m.p.h. for a wheel load of 50 lb., to meet this on a 250,000 lb. machine would demand a $-Kb_2$ of less than 0.01. Conventional balancing methods could not cope with the problem of holding consistently such a fine degree of balance.

It was pointed out, when dealing with "repeatability" in para. 2.8, that two solutions are open to us, namely,

(i) Power operation.
(ii) The spring tab.

For the very large aircraft under discussion, however, the spring tab no longer comes into the picture. On running out practicable design estimates, it will be found that the spring rate required is so small that the spring has virtually disappeared, leaving us with a type of servo tab system, i.e., a system in which the control is free to float, and the pilot's cockpit control merely operates the tab. Thus our two solutions for the very large aircraft become:—

(i) Power operation.
(ii) Servo tab.

At present opinion strongly favours power operation. The authors would, however, like to put in a plea that the alternative solution of manually controlled servo tabs should not be completely overlooked. On paper pure servo tabs should be capable of dealing satisfactorily with the control force problem on all three controls up to an all-up weight of at least 500,000 lb. The argument of lag in response with a servo tab system is sometimes raised, but technically it is difficult to demonstrate that any serious lag would arise provided the tabs were effective for small movements. The major objection to the servo tab is weight. In order to safeguard against flutter both tab and control surface must be mass balanced. This involves an appreciable weight penalty compared with a power operation scheme. Against this, however, must be placed the advantages of simplicity and reliability. Looked at from all angles it would seem reasonable to consider the pure servo tab system as a possibly successful rival to power operation.

PART II

THEORY AND EXPERIMENT

5. *Introduction*

Although control design is still far from being straightforward it is not quite such the hit or miss affair it was, and much advance has been made in the methods of estimating of control characteristics, and in the understanding of the principal phenomena connected with controls. The accumulation of experimental data from wind tunnel and flight tests, although apt to be confusing at times, has helped considerably in the formulating of a general correlating theory.

Two phenomena stand out from the experimental data:—

(1) Any increase in boundary layer thickness from whatever cause has only a small effect on the control properties when the control section is thin or concave. But convex or thick section controls are often greatly affected by comparatively small changes in boundary layer thickness.

(2) Small modifications at the trailing edge, particularly the adding of trailing edge strips or rounding of a thick trailing edge have very large effects on control balance, associated with changes in circulation for given incidence and control angle.

In what follows we shall attempt to present in a collected form the advances made in the theory of control design. The development of the theory is traced; semi-empirical analyses of the wind tunnel data are also presented, since until a more complete theory is developed the aircraft designer must rely on such methods for estimations.

6. *The Lift and Hinge Moments of a Control Surface (Linear)—General Theory*

We shall first treat the case involving small angles of incidence and control deflection; under these conditions the hinge moments can be taken as linear. The earliest attempt at calculating the lift and the hinge moments on an aerofoil with a hinged flap was made by Glauert and described in R. and M. 1095. Glauert's method consisted of regarding the aerofoil as being of small thickness and, therefore, replaceable by its skeleton—a straight line. Replacing the co-ordinate x by θ such that

$$x = \tfrac{1}{2} c\ (1 - \cos\theta)$$

The vorticity distribution over the aerofoil is defined by

$$k = 2V\ \{\ A_0 \cot \tfrac{1}{2}\theta + \sum_1^{\infty} A_n \sin n\theta\ \}$$

Where the first term refers to the undisturbed straight line and the Fourier series takes account of the deviation from the undisturbed state due to the control deflection.

The coefficients of the Fourier series are next identified using the geometrical relationships appropriate to the system. Having thus expressed a vorticity distribution in terms of the incidence and control angle, it is possible to derive expressions for the total lift, the lift on the control and the moment of the control about its own hinge. Detailed calculations are given in Appendix I. The main drawbacks to Glauert's theory are:—

1. It does not take cognisance of the boundary layer.
2. No account is taken of the finite thickness of the aerofoil.

The theoretical values of the invariants with aspect ratio b_1/a_1 and $b_2 - b_1 a_2/a_1$ are plotted against E in Fig. 12. The experimental results for the N.A.C.A. 0009 aerofoil are given for comparison.

In recent years the need for a theory which overcomes both these shortcomings has been emphasised by the results obtained in experimental work on the convexing and hollow grinding of control surfaces, and on the effects of small modifications to the trailing edge, *e.g.*, adding of trailing edge strips, and changes of transition point. Such modifications produce somewhat startling changes, especially in the hinge moments of the controls tested. These exploratory experiments on the effects of modifications of control profile are described in Refs. 4, 5, 6, 7, 8, 9. The results of the experiments can be summarised broadly thus:—

> Thickening the control section (*e.g.*, convex section) makes b_1 and b_2 more positive and is invariably responsible for a falling off of a_1 and a_2; conversely, modifications which increase control heaviness, *i.e.*, make b_1 and b_2 more negative, increase a_1 and a_2.

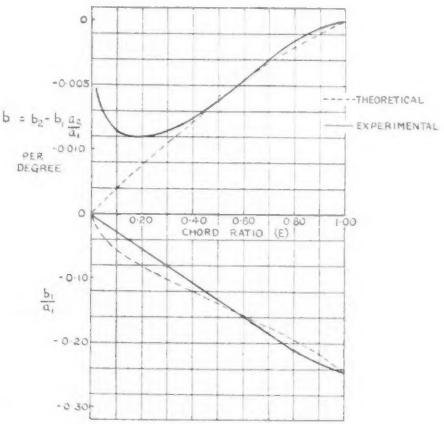


Fig. 12
Comparison of thin aerofoil theory and experimental results on N.A.C.A. 0009 aerofoil section.

Recently a step forward has been taken by Dr. Preston, of the N.P.L., as described in A.R.C. Report No. 6,732. The problem treated in this paper is the approximate calculation of the lift of symmetrical aerofoils taking into account the boundary layer. The connection and application of this to control problems is self evident.

Model experiments, Refs. 10, 11 (see Fig. 13), have demonstrated that the large effects of boundary layers on control moments are associated with changes in circulation round

the aerofoil and so any theory which will enable us to understand the properties of control surfaces must first aim at the calculation of these changes of circulation. Preston uses a theorem first put forward by Prof. G. I. Taylor as a basis of his calculations. This theorem states that equal positive and negative amounts of vorticity must pass into the wake at the trailing edge in the steady state. A proof of this theorem will be found in Appendix II. It can be easily shown that to a first approximation this condition is fulfilled when the velocities at the edges of the upper and lower boundary layers at the trailing edge are equal. Owing to the pressure rise from the edge of the wake to the trailing edge on two sides being different, and since there can be no discontinuity of pressure in the wake, the velocities generally differ slightly. Another assumption made by Preston is that the velocity field near the edge of a boundary layer is approximately that of potential flow round the aerofoil without boundary layer effects. Empirical corrections to these approximations are later introduced.

Calculations making no allowance for the effect of boundary layer and wake on the external potential flow, using Howarth's conditions for fixing the circulation, show that the effect of the boundary layer and wake on the external potential flow at the edge of the boundary layer is important. Two empirical corrections are, therefore, introduced. The first consists of a correlation of the discrepancy between the calculated velocities and the experimentally determined velocities at the edge of the boundary layer at the trailing edge of the aerofoil, with the boundary layer thickness

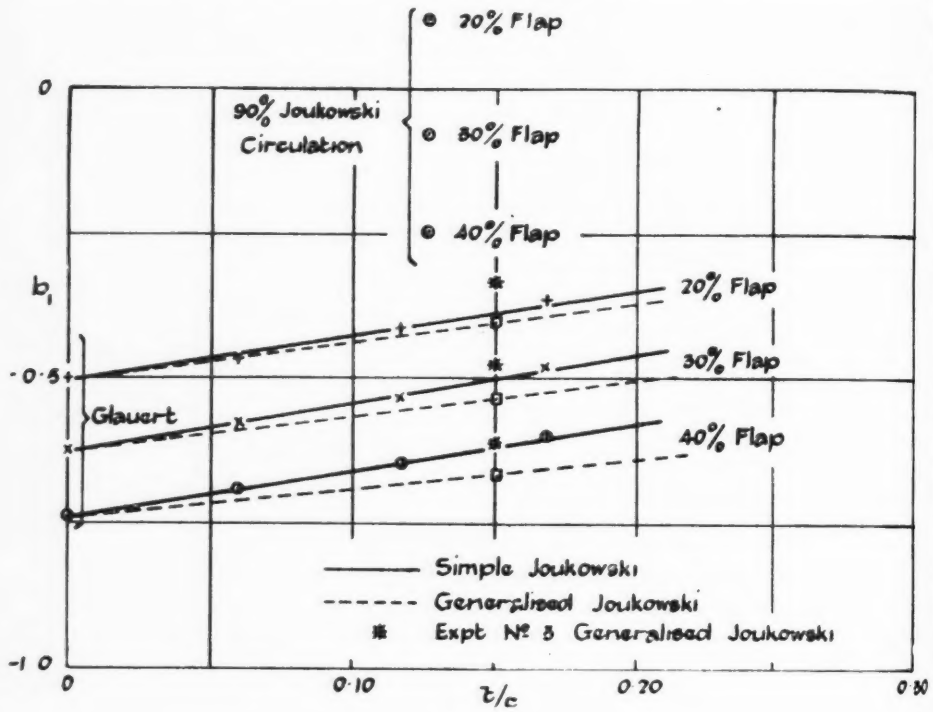


Fig. 13

b_1 as a function of t/c for various flap/chord ratios.

at the trailing edge. This simple form is unsuccessful in bringing the theory into line with experiment at various incidences. The correction is, therefore, re-arranged and split into two parts. The first, strictly applicable at 0°, is

$$\Delta_1 \frac{h^2}{U_o^2} = 1.433 \left(\frac{\delta}{c}\right)_m$$

applied to both sides of the trailing edge and at all incidences. $(\delta/c)_m$ being the mean δ/c for the two sides of the trailing edge. The second correction which is dependent on aerofoil shape is given by

$$\Delta_2 \frac{h^2}{U_o^2} = 0.0080\, \alpha^\circ.$$

This tends to reduce the value of K whilst the first does not affect the value of K, but improves the estimation of the velocities at the edge of the boundary layer at the trailing edge; the correction, therefore, gives what is required because the effects of wires, cords, etc., are already amply accounted for in calculations with the basic assumptions. Whilst the first correction appears plausible, the second can at the moment only be justified by results. The second empirical allowance for the effects of the boundary and wake on the velocities consists of using the experimentally determined value of the ratio of the velocities at the upper and lower edges of the boundary layer to fix the circulation. The best agreement with experiment is obtained with the last mentioned approximation. This theoretical investigation gives us an insight into the results of the experiments mentioned above. The hinge moments are critically dependent on the circulation, which in turn we have seen is mainly determined by the velocities at the edge of the boundary layer at the trailing edge. Thus, anything which modifies these velocities in an unequal manner will result in the change of circulation until the conditions of Prof. G. I. Taylor's theorem are fulfilled, that is, until equal positive and negative vorticity pass into the wake. Changes of the control profile, trailing edge strips or cords, bluff trailing edges, all result in such changes of velocities. Consider, for example, the case of trailing edge strips. The general effect might be expected to result in an increase in velocity along a normal to the streamlines at the trailing edge, the velocity becoming larger as the strip is approached, and vanishing at infinity. However, the upper boundary layer is thicker than the lower, so the addition of trailing edge strips produces a larger increment of velocity at the edge of the lower boundary layer and this in turn necessitates an increase in circulation to maintain the original ratio of the squares of the velocities at the upper and lower edges of the boundary layer. The theory, therefore, offers a qualitative explanation of the observed facts, but Preston has shown that the quantitative results of the theory are in poor agreement with experiment. This is probably because the separation of the flow downstream of the strip and the velocities in the boundary layer near the strip have important consequences.

The important effects of transition movements are well illustrated on the lines of the calculations. The effects are very pronounced for the thicker aerofoils.

Having determined the value of the circulation and hence the ratio of a_1 to a_{1T}, Preston attempted to relate the ratios a/a_{1T} and b_1/b_{1T}. In Fig. 14 (taken from Ref. 3) a single curve is drawn through the points, but it is now considered that this is too drastic a simplification as the results may, for different transition conditions and Reynolds numbers, separate into different curves for different sections. The analysis does not cover the case of the rate of change of hinge moment with control angle. It is hoped that it may soon be possible to develop a theory which will enable the hinge moment to be expressed in a more generalised form, indicating the nature of the variation of the hinge moment with the leading parameters (chord ratio, trailing edge angle or an equivalent parameter, balance, etc.).

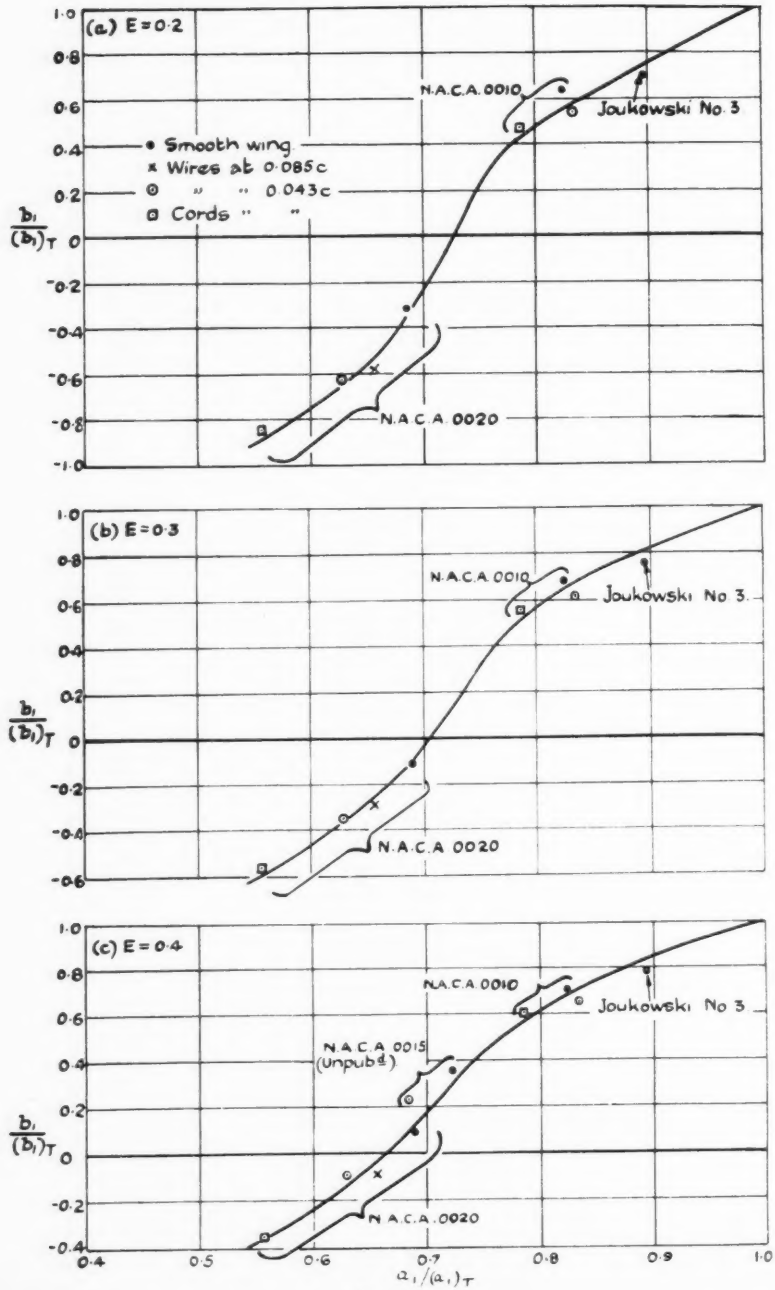
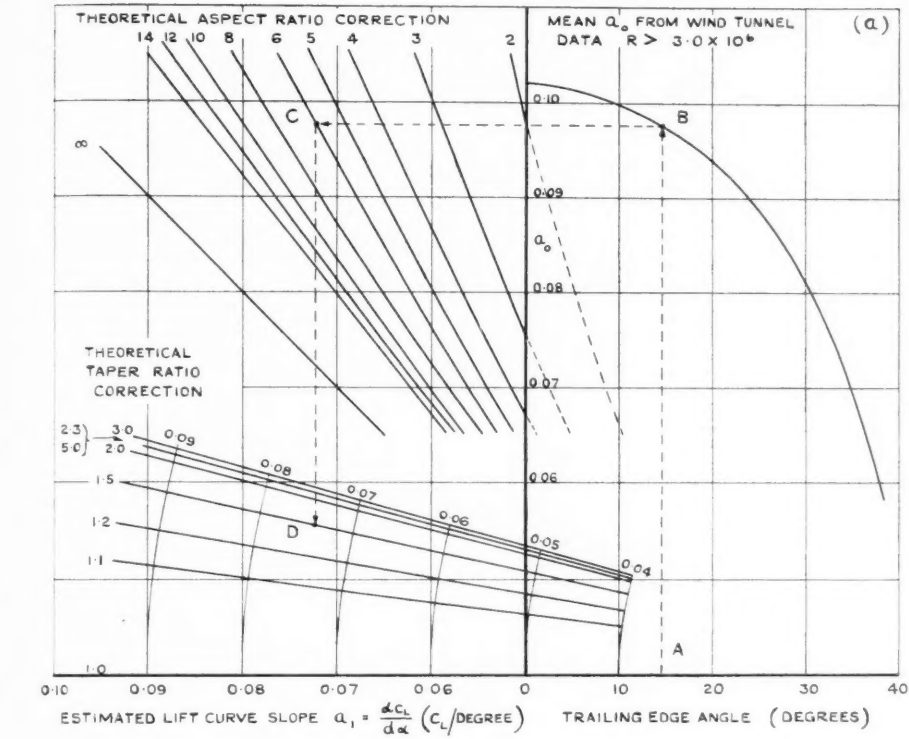
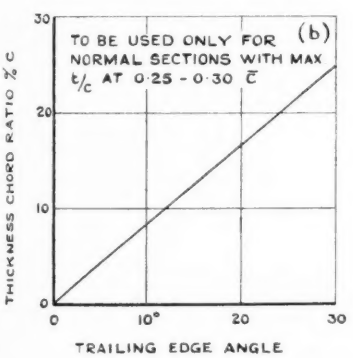


Fig. 14

$b_1/(b_1)_T$ as a function of $a_1/(a_1)_T$ for various flap/chord ratios and different aerofoils.





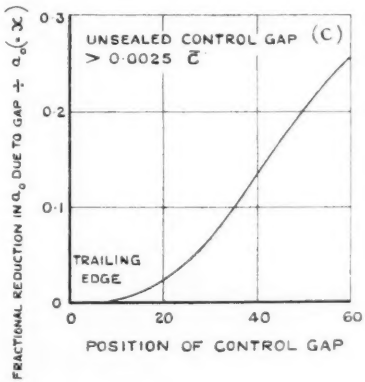


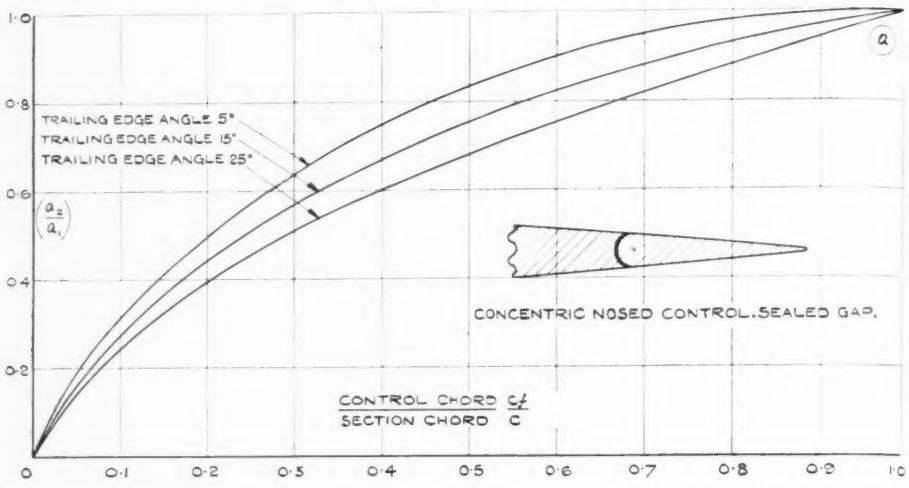
Fig. 15

(*a*) Chart for estimating aerofoil lift curve slope.
(*b*) Normal relationship between section thickness and T.E. angle.
(*c*) Reduction in aerofoil lift curve slope due to full span control gap.

METHOD OF ESTIMATION.

The line A.B.C.D. indicates the method used for estimating a_1. The aerofoil used in this example has:—(A) T.E. angle=14.7°, (C) aspect ratio=6, (D) taper ratio=1.5, giving a_1=0.074 C_L/°. If the aerofoil had a control gap > 0.0025 $\bar{c}$ at 0.50 of the wing chord, the a_o would be reduced by 20% and therefore a_1 would be 0.0655.

CHART FOR ESTIMATING THE AEROFOIL LIFT SLOPE, $dC_L/d\alpha$ PER DEGREE.



VARIATION OF $\frac{a_2}{a_1}$ WITH CONTROL CHORD & TRAILING EDGE ANGLE. FOR FULL SPAN CONTROLS

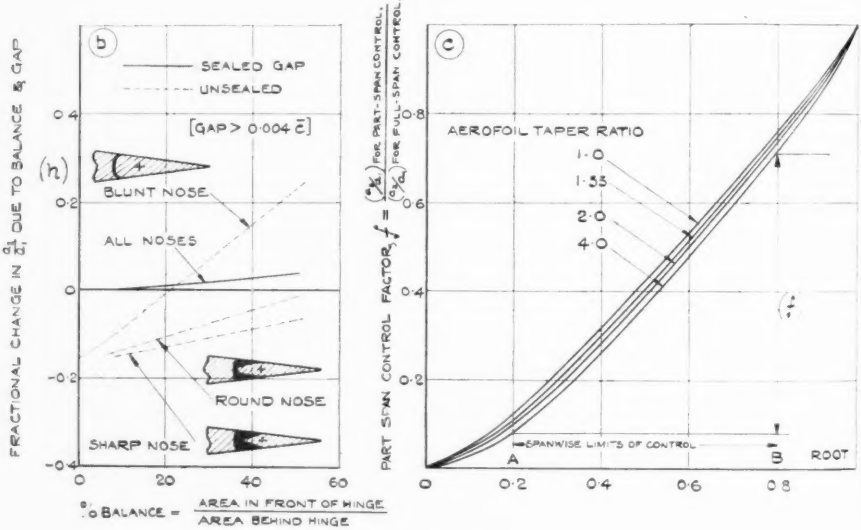


Fig. 16.

(*a*) Variation of a_2/a_1 with control chord and trailing edge angle for full span unbalanced controls.

(*b*) Change in a_2/a_1 due to full span balance.

(*c*) Factor for determining a_2/a_1 for a part span control.
For method of estimating a_2/a_1 for various contro's see Ref. 12.

CURVES FOR ESTIMATION OF a_2/a_1.

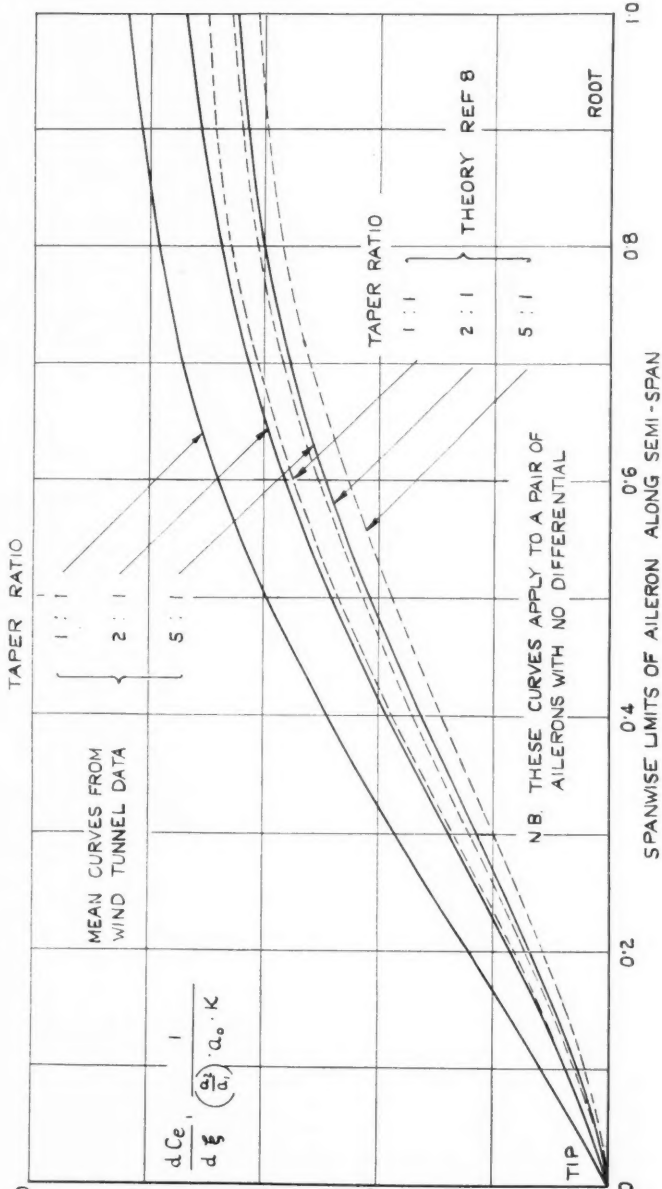


Fig. 17.

Aileron rolling power coefficient comparison of experimental mean curves with theory.

7. *Control Power*

The most satisfactory summary of existing theoretical and experimental results on control power is that of Ref. 12.

The main results are given in Figs. 15, 16, 17. It is seen that the factors mainly affecting the control power and a_2/a_1 are

1. The chord ratio.
2. The spanwise limits of the control.
3. The trailing edge angle.

The theory underlying the curves for the rolling moment due to aileron is to be found in Ref. 13.

It is important to note that when tabs are fitted due allowance should be made for the loss of lift incurred by deflection of the tab in the opposite sense to the control, that is, a_2/a_1 must be replaced by $a_2 - ka_3/a_1$ where k is the tab gearing.

The theory of the response of an aeroplane to aileron application has been treated by Gandy in Reference 31, with particular reference to the effect of variation of n_v and l_v. An outline of his theory will be found in Appendix VI, and a few curves from Reference 31 are reproduced in Fig. 18.

$C_L = 0.2$, $\mu = 10$.

Curve	n_v (Fin)	n_v	$-l_v$
a	0.048	0.024	0
b	0.048	0.024	0.06
c	0.048	0.024	0.12
d	0.072	0.048	0
e	0.072	0.048	0.06
f	0.072	0.048	0.12
g	0.12	0.096	0
h	0.12	0.096	0.06
i	0.12	0.096	0.12

$i_A = 0.06$, $i_c = 0.12$.

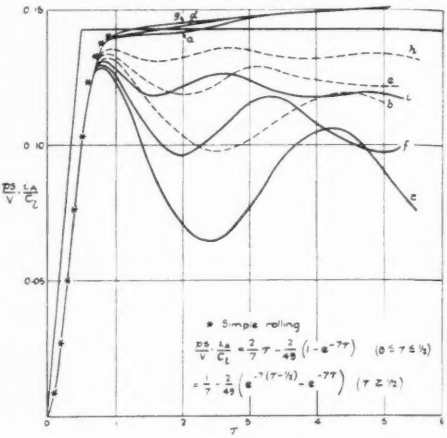


Fig. 18.
Aeroplane A. $C_L = 0.2$.
Rate of roll due to applied rolling couple.
Max. rolling couple reached in time, $\tau = 0.5$.

8. *Control Balance*

8.1. *General*

Nothing has so far been said about the control balance. The high degree of manœuvrability expected from present day aircraft often necessitates very close balance. It is in attempting to adjust and maintain such close balance that many of the difficulties of control design are encountered. Some progress in methods of estimation of the balance effect of the most commonly used types has been made. We will separate the balance effect from the remainder of the hinge moment, and express the hinge moment of the balanced control in the form

$$H = H_0 + \Delta H$$

where H is the hinge moment of the balanced control, H_0 is the hinge moment of the unbalanced control, and ΔH is the increment in hinge moment due to the balance.

Assuming the linearity of the hinge moments, this leads us to the conception of increments in the hinge moment slope.

8.2. *Set Back Hinge Balance*

In a recent work Thomas and Lofts have treated this form of balance by an extended form of the Glauert theory for thin aerofoils. (See Appendix 3.) A study of pressure plottings for noses of different shapes enable some allowances to be made for nose shape, as it was noted that, in general, the pressure peak occurs at the maximum ordinate of the nose section.* Thus insofar as the nose shape determines the position of this maximum ordinate and hence the position of the pressure peak, it is

* This result may not be generally true and needs confirmation by further experiment.

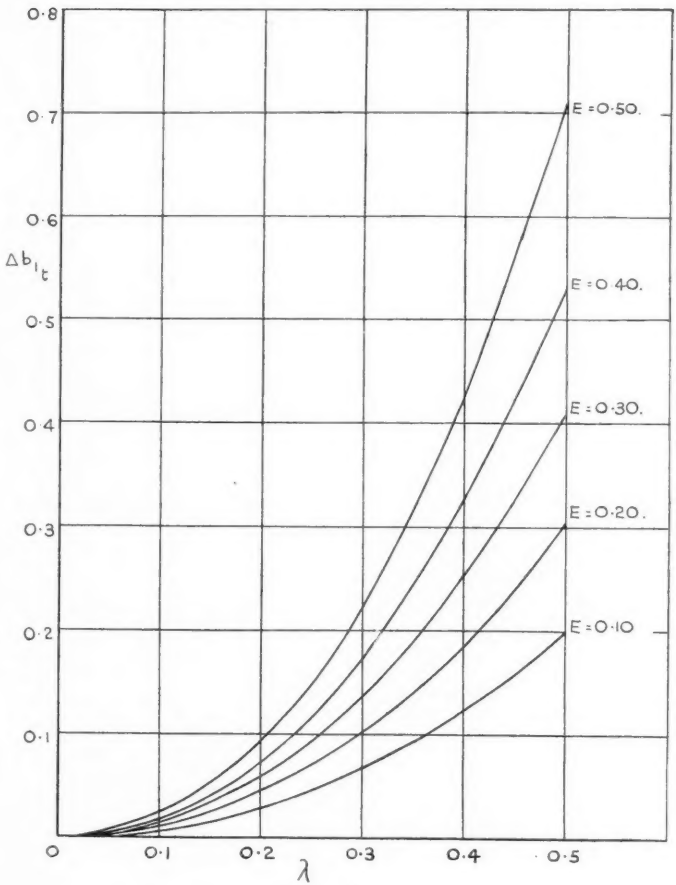


Fig. 19.
Theoretical variation of Δb_{1t} with E and λ.

possible to account for its effect on the hinge moments theoretically by breaking the aerofoil at this point and not at the hinge. Differences of nose shape which result in differences of the maximum pressure cannot be allowed for. Experimental and theoretical work such as are outlined in the preceding paragraphs suggest that correlation of such a theory with experiment should prove easier than for hinge moments of plain controls.

In its usual form the percentage balance of this type of control is defined as the area forward of the hinge over the aft of hinge. If this geometrical definition is strictly adhered to the plain round nosed control has a certain amount of balance depending upon the thickness of the aerofoil section and the chord of the control. Since the nose of a plain control is normally semi-circular it is usual to assume that its contribution to the hinge moment is nil, since the pressures pass through the hinge. The usual definition of balance can be replaced by what might be termed the "effective balance," defined by

$$\lambda = \{ (c_b/c_\eta)^2 - (t/c_\eta)^2 \}^{\frac{1}{2}}$$

in two dimensional flow.

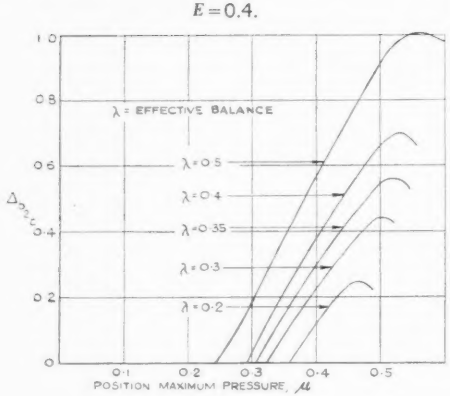


Fig. 20.
Theoretical variation of $\Delta_{b_2 t}$ with λ and μ.

It is seen that as the plain round-nosed control is approached the balance tends to zero. This definition would be expected to assist us in accounting for the effect of thickness. The theoretical values of the increments b_1 and b_2 (see Figs. 19-21) agree fairly well with experiment for the thin sections. Analysis of the experimental data on thicker controls enable corrections for the effects of thickness to be introduced.

The corrections can be expressed approximately in the form

$$\frac{\Delta b_1}{\Delta b_{1t}} = (1 - 4.9\,\tau^2)$$

all nose shapes and

$$\frac{\Delta b_2}{\Delta b_{2t}} = (1 - 10\,\tau^3)$$

for circular nose shape

$$= (1 - 4.3\,\tau^2)$$

for elliptic nose shape.

The suffix t refers to the theoretical value, and τ is the trailing edge angle (radians).

It is seen that for a small trailing edge angle (10°) the experimental value of Δb_1 is 85 per cent. of the theoretical, whilst the corresponding figures for Δb_2 for the two nose shapes are 95 and 87 per cent. respectively. The agreement of theory and experiment is therefore good for thin sections.

Similar empirical corrections are obtained for the effect of nose gap. In general unsealing the nose gap increases Δb_1 and Δb_2; for τ of about 10° the effect is small. When a general theory has been developed for the plain control it should prove a simple matter to extend this to cover set back balanced controls.

8.3. *Horn Balance*

Unlike the set back, the horn balance is not readily amenable to theoretical treatment. Concentrated as it is at the tip and therefore operating in complex flow conditions, it is unlikely that any simplified theoretical attack will prove successful. In a recent note Thomas and Lofts (14) have derived semi-empirical relationships for the increments b_1 and b_2 due to both the shielded and unshielded type of horn. An interesting point brought out by this analysis of the model data is the transition from

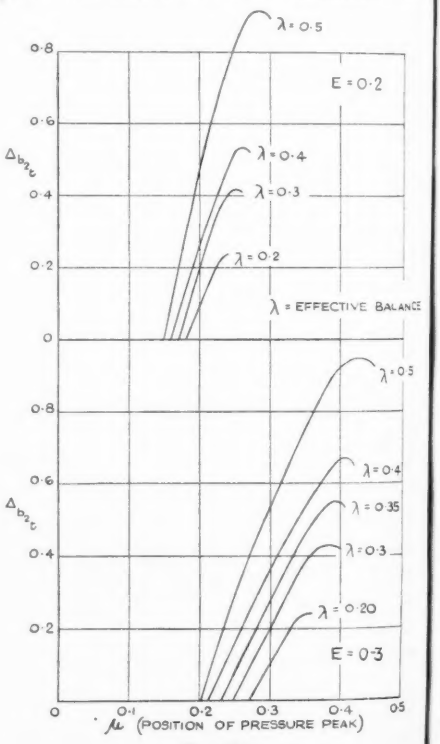


Fig. 21.
Theoretical variation of $\Delta_{b_2 t}$ with λ and μ.

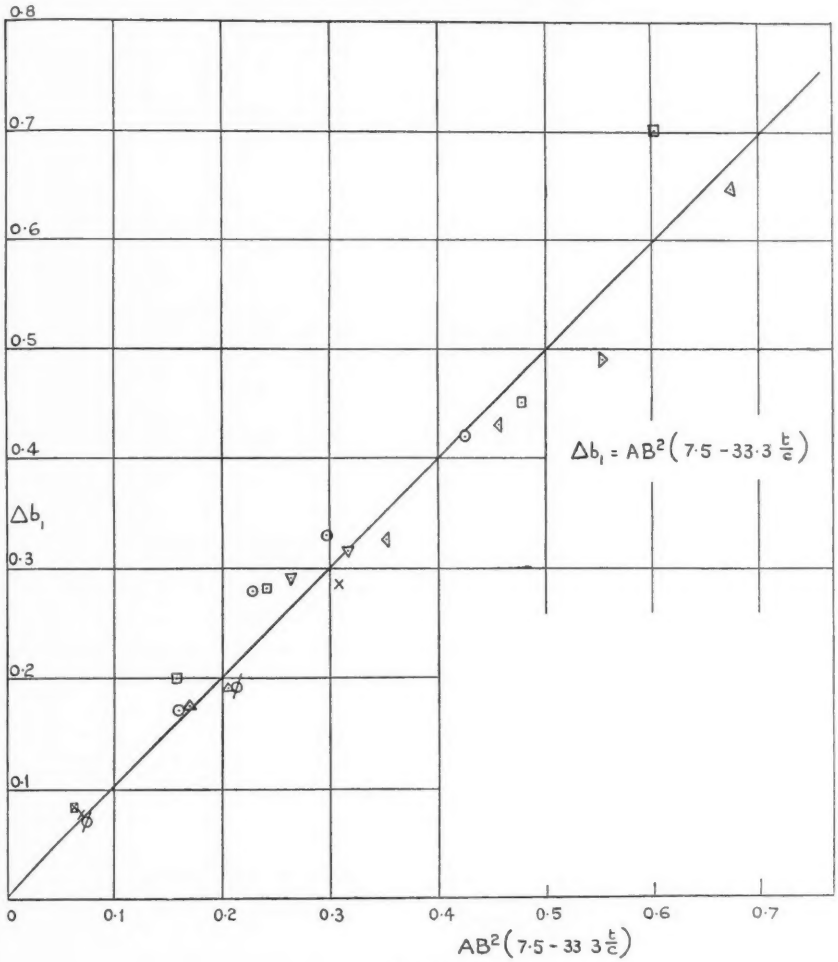


Fig. 22.
Increment in b_1 due to horn balance. Unshielded horns.

the shielded to the unshielded. As the chord of the horn balance is successively increased, the hinge moment contribution increases gradually at first and then when the nose of the balance is at approximately three quarters of the distance of the chord from the trailing edge there is a sudden increase in the balance contribution. Another interesting point is that the contribution due to sloping or partly shielded horns can be regarded as the sum of the increment due to the shielded and unshielded parts of which it is composed. The expressions derived for the increments b_1 and b_2 can be expressed mathematically as

$\Delta b_1 = AB^2\,(7.5 - 33.3\,t/c)$ } unshielded horns
$\Delta b_2 = AB^2\,(6.5 - 30.7\,t/c)$ } (see Figs. 22, 23).

$\Delta b_1 = AB^2\,(e^{x^3} - 1)\,(4.36 - 19.4\,t/c)$
for round and elliptic noses

$\Delta b_2 = AB^2\,(e^{x^2} - 1)\,(3.79 - 17.9\,t/c)$
elliptic nose

$= 1.286\,AB^2\,(e^{x^2} - 1)\,(3.79 - 17.9\,t/c)$
round nose

} shielded horns.

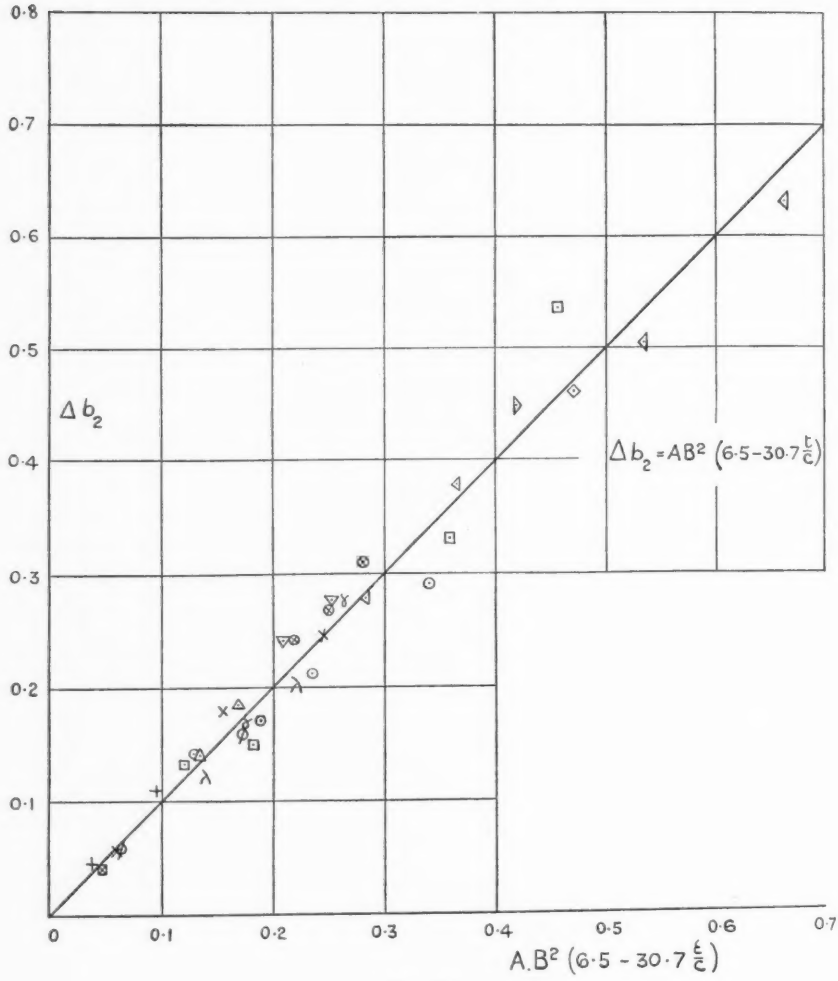


Fig. 23.
Increment in b_2 due to horn balance. Unshielded horns.

It is seen by substitution that for an average thickness of the order of 10 per cent. the increment in b_1 is some 25 per cent. greater than the increment in b_2. This well-known property of the unshielded horn is due to its location at the tip in the up-wash due to the tip vortices. There is some experimental evidence that shows that by shielding the tip from the rest of the main surface, it is possible to make the increments equal. This is so because the horn no longer distinguishes between an incidence and a control angle change.

Horn balance has often been successfully used in this country and has some advantages over other types of balance, these are:—

1. It is possible with a horn to obtain a zero or positive b_1.
2. It is relatively simple to modify the horn if the characteristics of the control are not satisfactory.

8.4. *Westland-Irving Balance*

This form of balance is a particular case of an internal balance in which the balance is provided by the difference in pressures at vents in the upper and lower surfaces of the aerofoil. In the Westland-Irving balance the vents are at the hinge line. Knowing the pressure distribution around the aerofoil with control neutral and deflected, it is possible to calculate the balance required (see the case of the generalised sealed balance, paragraph 8.5).

The increments in b_1 and b_2 for this type type of balance will depend mainly on the following parameters:—

(1) Effective balance

$$= \sqrt{\{(c_b/c_\eta)^2 - (t/c_\eta)^2\}}$$

c.f., set back balance.

(2) Chord ratio or more strictly the position of the vent.

In practice the nose gap may be sealed or unsealed. Unsealing reduces the effectiveness of the balance. Alterations in the vent size or cover plate alignment modify the hinge moment curves.

The advantages of this type of balance are—smaller drag, greater effectiveness if sealed, and balance over a fairly wide range of incidence and control angle. Against these there are the practical disadvantages of making an effective seal and avoiding alteration of balance by manufacturing errors in the vent size and cover plate alignment. The two later disadvantages can be overcome by combining this form of balance with a spring tab.

8.5. *Generalised Sealed Balance*

The form of balance described in the preceding paragraph is a particular application of the theoretical notion that b_0, b_1 and b_2 can be completely controlled by balancing the control by means of pressures taken from suitable points on the fixed surface. This viewpoint finds a strong advocate in Prof. G. T. R. Hill. In practice the balance mechanism can take various forms, for example, the balance surface may be a hinged plate or a piston; it may be separate from the control and, if the ducting problem can be solved, from the vents; it can be linked either to the main control or to a tab. The practical problems associated with this type of balance will be discussed later. The possibilities of the balance can, however, be simply stated if two vents only are considered, one on the upper and one on the lower surface of the aerofoil, because the maximum pressure difference is obviously obtained by having them on opposite surfaces. The suction σ on the upper surface at any point x may be written as

$$\sigma = \sigma_0 + \sigma_\alpha \cdot \alpha + \sigma_\eta \cdot \eta$$

where α is the incidence, η is the control angle, and σ_0, σ_α, σ_η are functions of x. Similarly for the pressure p on the lower surface at another point y.

$$p = p_0 + p_\alpha \cdot \alpha + p_\eta \cdot \eta$$

where p_0, p_α, p_η are functions of y. It is usual to express σ and p as fractions of dynamic pressure.

Case 1. *The Balance Surface Connected to the Main Control*

Here the increment in hinge moment is of the form

$$\lambda' [(\sigma_0 + p_0) + (\sigma_\alpha + p_\alpha)\alpha + (\sigma_\eta + p_\eta)\eta]$$

where λ' depends on the geometry of the system. Hence

$$\lambda'(\sigma_0 + p_0) = \Delta b_0$$
$$\lambda'(\sigma_\alpha + p_\alpha) = \Delta b_1$$
$$\lambda'(\sigma_\eta + p_\eta) = \Delta b_2$$

Similar relationships can be easily obtained for the case where the balance surface is connected to a tab whose hinge moment coefficient for moments about the tab hinge is

$$C_{Ht} = c_0 + c_1\alpha + c_2\eta + c_3\beta$$

These are

$$(b_3/c_3)[\mu'(\sigma_0 + p_0) - c_0] = \Delta b_0$$
$$(b_3/c_3)[\mu'(\sigma_\alpha + p_\alpha) - c_1] = \Delta b_1$$
$$(b_3/c_3)[\mu'(\sigma_\eta + p_\eta) - c_2] = \Delta b_2$$

An advantage of using a tab is the reduction in the size of the balancing mechanism. It has the following disadvantages:—

1. Critical dependence on tab hinge moment, about which little is known.
2. Tricky linkage design.

Given the pressure distribution around the aerofoil the above equations determine the increments in b_o, b_1 and b_2 for any given geometry of the balance mechanism.

The main facts about pressure distribution for conventional aerofoils can be summarised thus:—

1. σ_a, p_a, p_η, σ_η are all positive.
2. σ_η and p_η increase as x and y increase beyond about 0.2c being maximum at the hinge.
3. σ_a and p_a increase as x and y decrease, values at the nose of the aerofoil being critical and involving loss of linearity.

It is interesting to apply this theory to the particular form of sealed balance known as the Westland-Irving. It is clear from the results quoted that Δb_2 is greatest and Δb_1 least with the vents at the hinge, which is of course the case for this particular balance. Therefore, with close balance there will be a large response factor and loss of stability if such a balance is applied to an elevator or a rudder. Moving the vents forward increases the increment in b_1 and decreases the increment in b_2. It thus seems possible that by the use of a generalised sealed balance with forward vents b_1 can be kept under control, although in general it will be necessary to reduce b_2 still further by such means as geared or spring tab.

8.6. *Tab Balance*

8.61. *Geared Tab*

The balances previously discussed are purely aerodynamic balances. It is possible to balance a control by gearing a small movable rear portion, usually called the tab, to the main control, the tab operating in the opposite sense to the main control. The degree of balance can be varied by means of the gearing. The hinge moment of tabs about the control hinge can be estimated with a fair degree of accuracy by the methods of Lyons' note, Ref. 15. The b_1 for the control remains practically unaltered, the balance being effected by a reduction in the effective b_2 which becomes $b_2 - kb_3$.

Balance by means of a geared tab can therefore be associated with a large response effect, which further increases the effective balance in the case of ailerons. There are limitations on balance by this means as if overdone it produces undesirable stick force characteristics. These effects are discussed in Ref. 16.

8.62. *Spring Tab*

This has already been discussed in para. 2.8 of Part I. The general theory of a spring tab layout is given briefly in Appendix 4. A fairly full account of spring tab developments to date will be found in Ref. 17.

8.7. *Mechanical Balance*

8.71. *Aileron Swinging Weights*

A mechanical scheme for lightening ailerons discovered from an examination of a captured Ju. 88 is described in Ref. 18. Swinging weights in the wings near the wing tips are so coupled to the ailerons that the centrifugal forces on the weights when the aeroplane rolls tends to lessen the pilot's effort. Theory indicates that the balancing effect of such a device is approximately proportional to the cube of the aileron angle, and should, therefore, be very effective in reducing the stick force for large aileron angles. It is easily seen, since the centrifugal force on the weight is proportional to p^2, where p is the rate of roll, that at a given V_1 the balancing effect increases markedly with height. This, of course, forms the main drawback to the scheme. Fig. 24 illustrates the stick force aileron angle relationship for such a device.

8.72. *Variable Gearing*

Since the stick force is proportional to the gearing of the control to the stick, the stick

force characteristics can be varied theoretically between very wide limits provided some means of adjustment can be found for the gearing. For example, an attractive idea is automatically to vary the gearing with airspeed in such a manner as to ease the pilot's loads at high airspeeds.

Although attractive because of its ex-

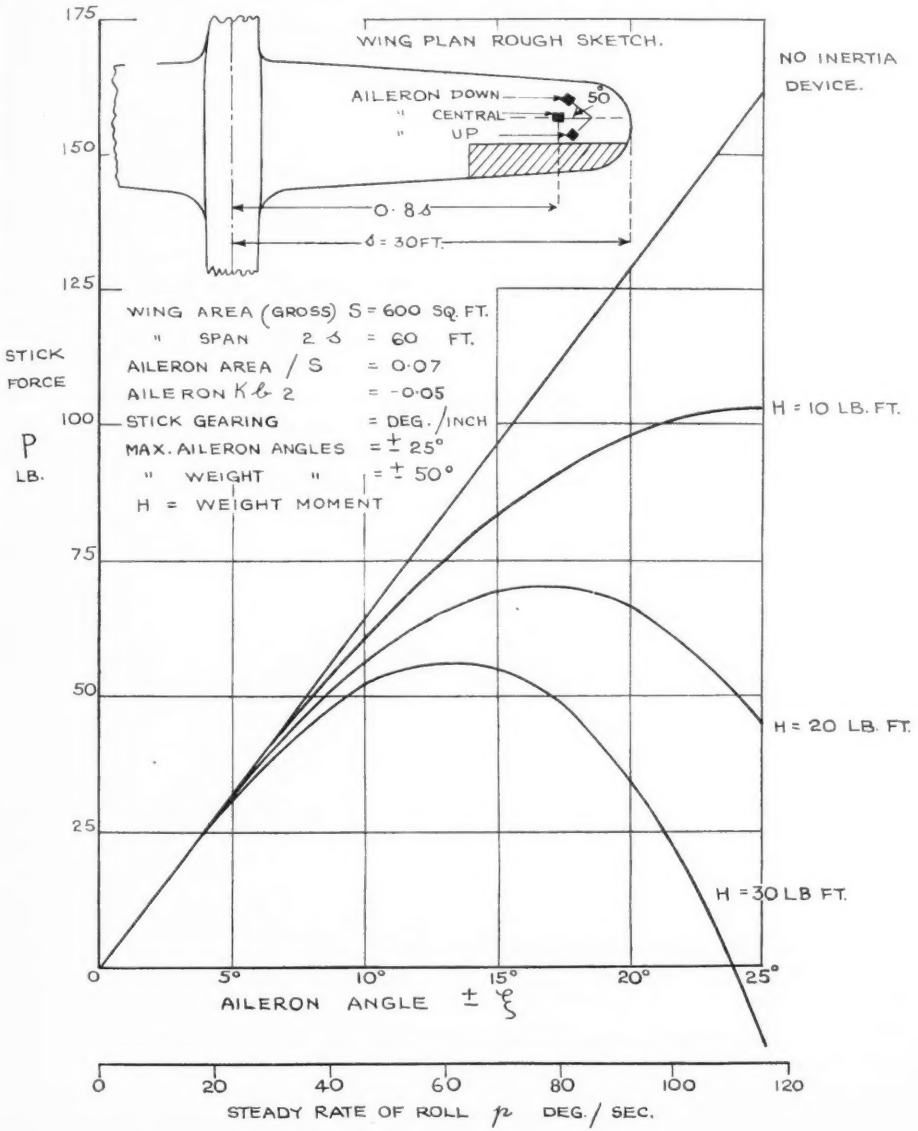


Fig. 24.
Effect of aileron inertia device on stick forces at 250 m.p.h. V_T at 15,000 ft.

treme flexibility, such a variable gearing is at a disadvantage compared with the spring tab on the score of mechanical complexity.

8.73. *Differential Gearing as a Means of Balance*

Some theoretical and flight investigations suggest that differential gearing, combined with adjustment of aileron floating angle by means of a tab, makes a powerful method of balancing ailerons. Theoretically it is possible to obtain close balance over the entire speed range more directly by differential balance than by any other means, provided the differential and the tab setting are nicely adjusted to the natural floating properties of the aileron. Thus, if the aileron floats up as incidence increases a downward differential must be used combined with an upward set tab, while if the aileron floats down as the incidence increases an upward differential must be used combined with a down set tab.

Where differential has been used in the past it was restricted to upward differential aimed at improving the aileron rolling and yawing movements at large displacements and large incidence, the aileron being balanced mainly by other means; since no more than the natural floating angle is used, the differential balance at high speed is feeble and may be of either sign. Since in general an unbalanced aileron has a negative b_1 and can only be given a positive b_1 by aerodynamic balance, the designer who decides to balance such an aileron by differential is virtually committed to a downgoing differential combination with an upward set tab. The pros and cons of such a scheme can be summarised as follows:—

On the credit side:—

1. A direct attack on the main objective, which is close balance at high speed with somewhat coarser balance at large displacement at low speed.
2. Suppression of troubles arising from non-linearity of hinge moments when other forms of balance are used.

On the debit side:—

1. Some loss of rolling moment and increase in adverse yawing moment.
2. Increases in the load in the control system due to the tab.

The theory is given in Appendix 5.

8.74. *Aerodynamic Booster*

Another form of mechanical balance, which has not received much detailed consideration, consists of feeding into the control circuit by a cylinder and cam mechanism force proportional to the dynamic pressure and to the control angle. In theory, there is a large choice of the degree of balance obtainable.

9. *The Linearity of Hinge Moment Curves*

It has been tacitly assumed above, at any rate in the theory, that the variation of the hinge moment of a control with incidence and control angle is linear. It is well known that such linearity often exists only over a limited range of control angle. Preliminary examination of wind tunnel data indicates that a main factor determining the degree of the non-linearity is the trailing edge angle; other parameters affecting the shape of the hinge moment curve are:—

The chord ratio of the control.
Size of the nose gap.
The nature of the balance.

Some idea of how the last mentioned affects the shape of the hinge moment curve of the balanced control can be obtained from Fig. 25 abstracted from Ref. 14. Figs. 26, 27 provide an excellent illustration of the relation between the curvature of the hinge moment curve and the magnitude of the trailing edge angle. An increase in the chord ratio of the control affects the curvature of the hinge moment curve; this is illustrated in Figs. 26, 27. Generally the effect of nose

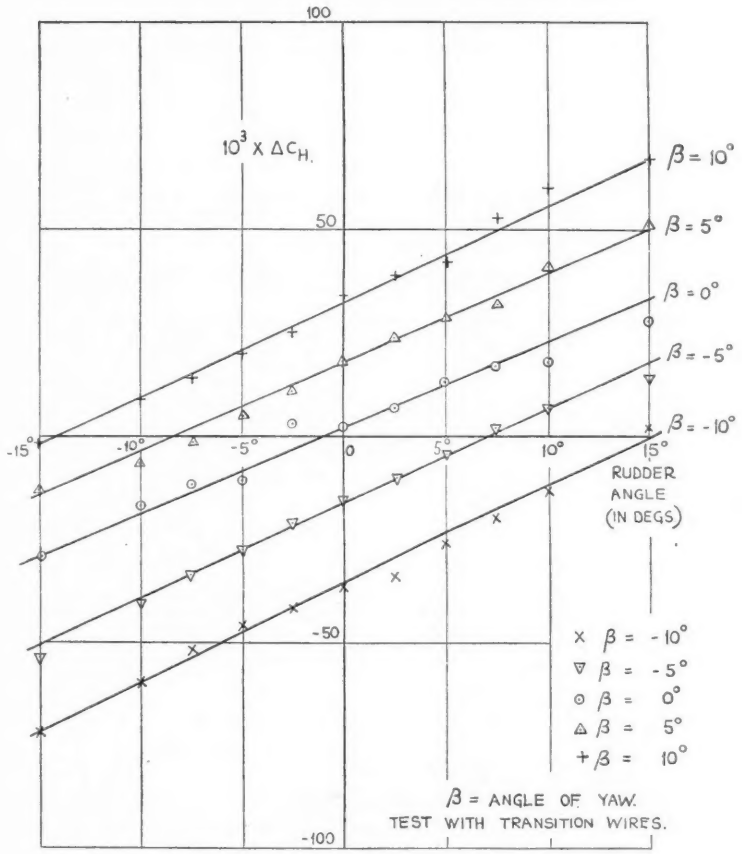


Fig. 25.
Increment in C_H of rudder due to adding horn balance.
Unshielded horn.

gap is to cause an earlier breakdown of the flow and to increase the curvature of the hinge moment curve. From the figures mentioned above it follows that the effect of the curvature can put the theory in serious error at control angles above 10° even at small or moderate trailing edge angles; in such a case the hinge moment at 10° control angle is some 30 per cent. larger than that estimated on the linear basis. It is, therefore, desirable that some method should be developed for the estimation of hinge moments at large incidence and control angles, and that attention should be given to devices designed to defeat the bad effects associated with non-linearity of the hinge moment curves.

10. *Aspect Ratio Corrections*

In the preceding paragraphs we have mainly been interested in the control in two-dimensional flow. In order to apply these results to aeroplane design it is necessary to correct for the effect of aspect ratio. The simplest and most easily derived correction is that of the lifting line theory; on the basis of this theory it can be readily established that the following quantities are

independent of aspect ratio, a_2/a_1, b_1/a_1, $b_2 - b_1 .(a_2/a_1)$. This simplified treatment is probably satisfactory for a full span control such as we have in general in the case of elevator and rudder, but not for part span controls such as ailerons.

The lifting line theory assumes that the downwash is constant along the chord, or, in other words, that the chordwise distribution of resultant pressure at a section of a wing of finite aspect ratio corresponds to that of two dimensional flow for a lower incidence. The distribution of downwash varies along the chord and it follows that the quantities mentioned above in fact vary slightly with aspect ratio. This has very little effect on the total lift, but for small aspect ratios introduces errors in the hinge moments.

It is possible that lifting-surface theory,

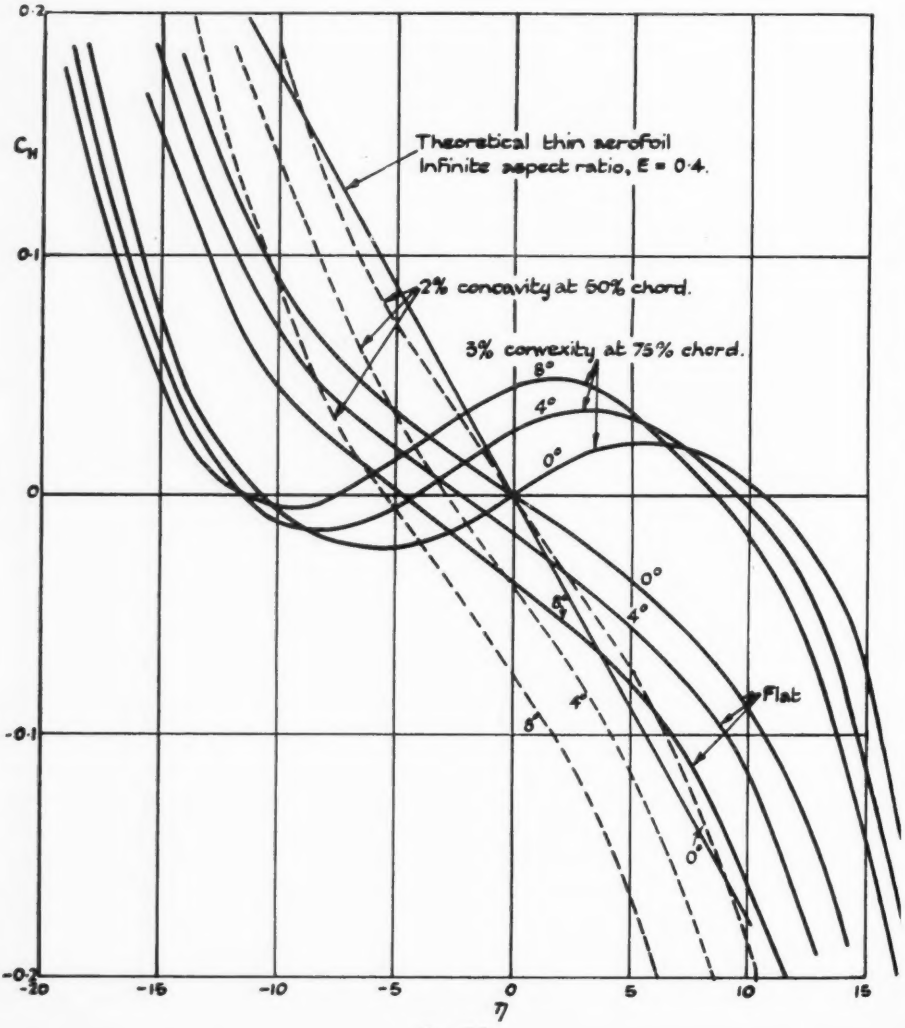


Fig. 26.

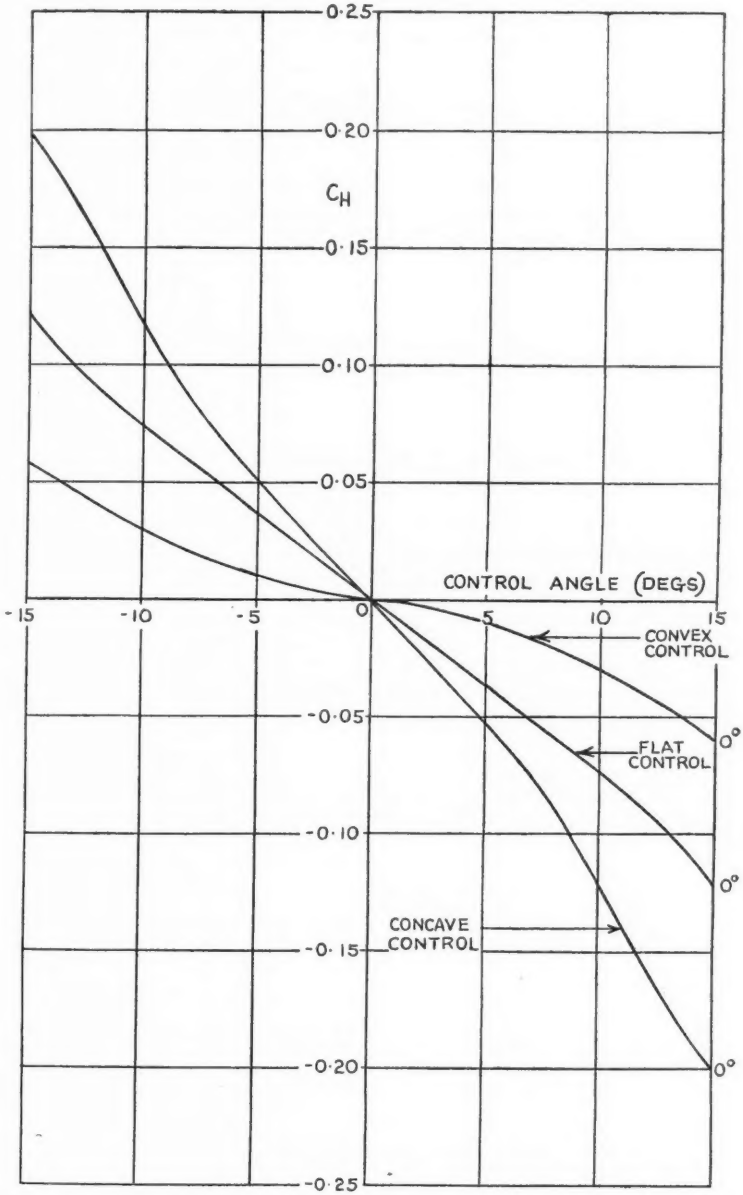


Fig. 27.
Hinge moments of 20% chord control of various profile shape (N.A.C.A. 0015 aerofoil).

or empirical corrections to the lifting-line theory, will provide methods by which hinge moments in three dimensional flow and for small aspect ratios can be determined.

11. *Compressibility Corrections*

The speeds of some modern aircraft are well within the compressibility region, and in the aerodynamic and structural design of control surfaces due allowance must be made for the effect of compressibility on the aerodynamic characteristics. The general theory of compressible flow is well known and established, and can be summarised in the Glauert Law.

$$p_c = p_i / \sqrt{(1-M^2)}$$

or the more exact law of Von Karman

$$p_c = p_i \Big/ \left[\sqrt{(1-M^2)} + \frac{M}{1+\sqrt{1-M^2}} \cdot \frac{p_i}{2} \right]$$

The lift and hinge moment coefficients are, therefore, in two dimensions increased in the ratio $1/\sqrt{(1-M^2)}$ on Glauert's theory.

In application to design it is important to allow for the effect of aspect ratio; the theory as developed by Glauert has been modified by Young and Owen (19) to account for this effect. The results can be summarised in the following formulæ for the first order effect of compressibility.

$$\frac{B_1}{b_1} = \frac{A_1}{a_1} = \frac{A_2}{a_2} = \frac{A_3}{a_3} = \gamma = \frac{(1+a_{10}/\pi\Lambda)}{(\beta + a_{10}/\pi\Lambda)}$$

$$\frac{B_2}{b_2} = \frac{\gamma}{\beta} \cdot \mu_2$$

$$= \frac{\gamma}{\beta} \cdot \left\{ \frac{\beta + \dfrac{a_{10}}{\pi\Lambda}\left[1 - \dfrac{b_{10}}{b_{20}} \cdot \dfrac{a_{20}}{a_{10}}\right]}{1 + \dfrac{a_{10}}{\pi\Lambda}\left[1 - \dfrac{b_{10}}{b_{20}} \cdot \dfrac{a_{20}}{a_{10}}\right]} \right.$$

$$\frac{B_3}{b_3} = \left(\frac{\gamma}{\beta}\right)\mu_3 \fallingdotseq \frac{1}{\beta}$$

It has been shown in Ref. 20 that the downwash for compressible as well as incompressible flow is given by the equation:

$$\frac{w}{u} = \frac{C_L}{\pi\Lambda}$$

This, together with the usual assumption that in terms of the local effective incidence (α_{10}) conditions at any point along the wing are two-dimensional, forms the basis of the analysis. The results quoted above follow quite readily. Details of the calculation are given in Refs. 19, 20. The particular case of ailerons is considered in Ref. 21 and it is shown there that in general any refinements to the simple two-dimensional theory will probably be unnecessary. Insufficient experimental data are available to test the theory fully. Such data as there are seem to indicate that the theoretical corrections are in reasonable agreement with experiment for sealed controls below the shock stall. Unsealing the gap greatly modifies the control characteristics so that the agreement is no longer as good.

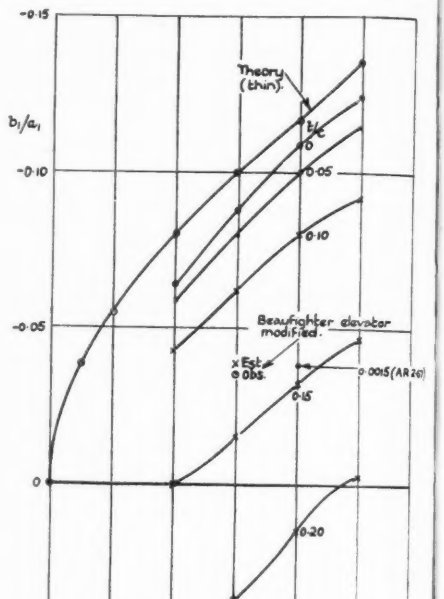


Fig. 28.

12. *Summary of the Theoretical and Experimental Data Useful for Design*

Collections of data, theoretical and experimental, which will prove useful in the

general design of control surfaces are described below.

12.1. *Control Lift*

An extremely useful collection of data on the lift generated by a control is to be found in Naylor and Lyons' Note, Ref. 12. The main curves for use in estimation of the coefficients a_1, a_2 and a_3 are reproduced here as Figs. 15, 16, 17.

12.2. *Hinge Moments of Plain Controls*

No entirely satisfactory method of estimation is in existence for the hinge moments of plain controls, although a good deal of experimental information of a rather mixed character is in existence. An analysis of hinge moment data on plain controls is contained in a paper by Bryant, Ref. 22. The curves he obtained demonstrate certain general trends, viz., that b_1 and b_2 both

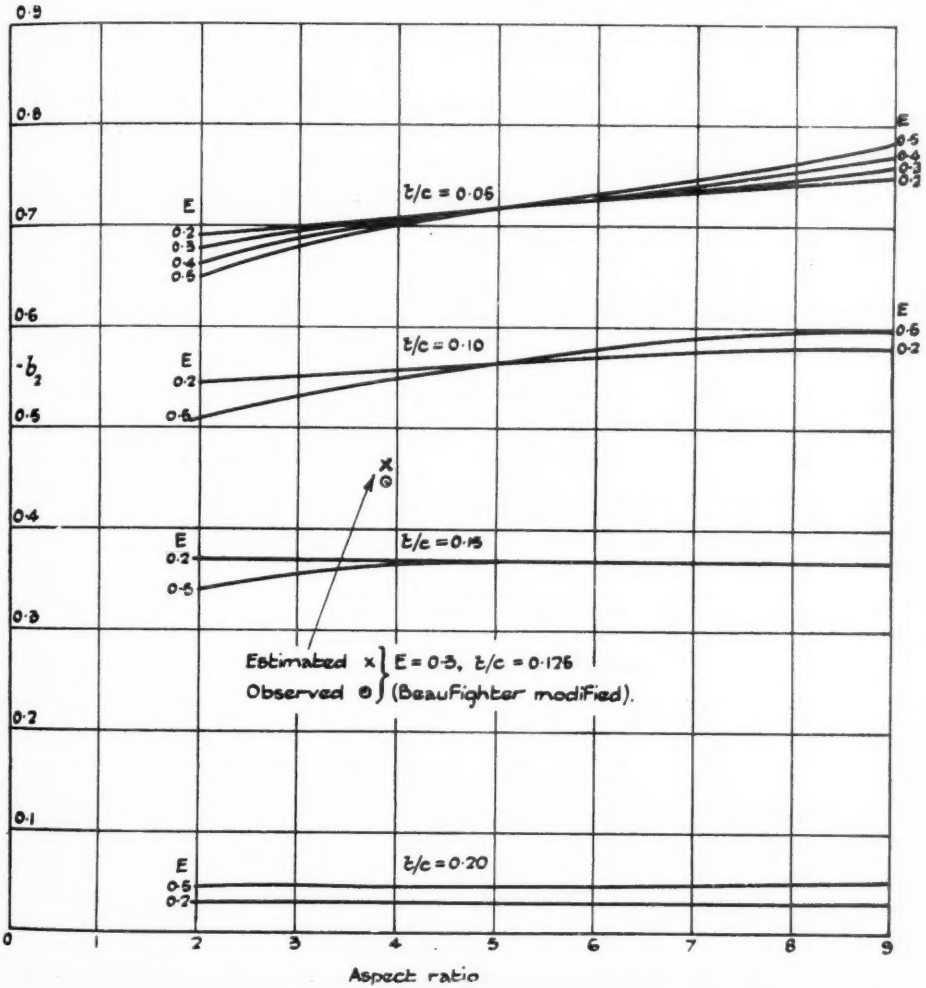


Fig. 29.

NOTE:—The coefficients apply to flat sided controls with radius-nose, sharp trailing edge, and transition of aerofoil far forward.

become increasingly positive with increase of trailing edge angle; also that b_1 becomes more positive with decrease of chord ratio, whilst b_2 is less sensitive to change of chord ratio (see Figs. 28, 29).

Later attempts are not yet published because of their incomplete nature. One difficulty is distinguishing between true scale effect and the effects of transition movement.

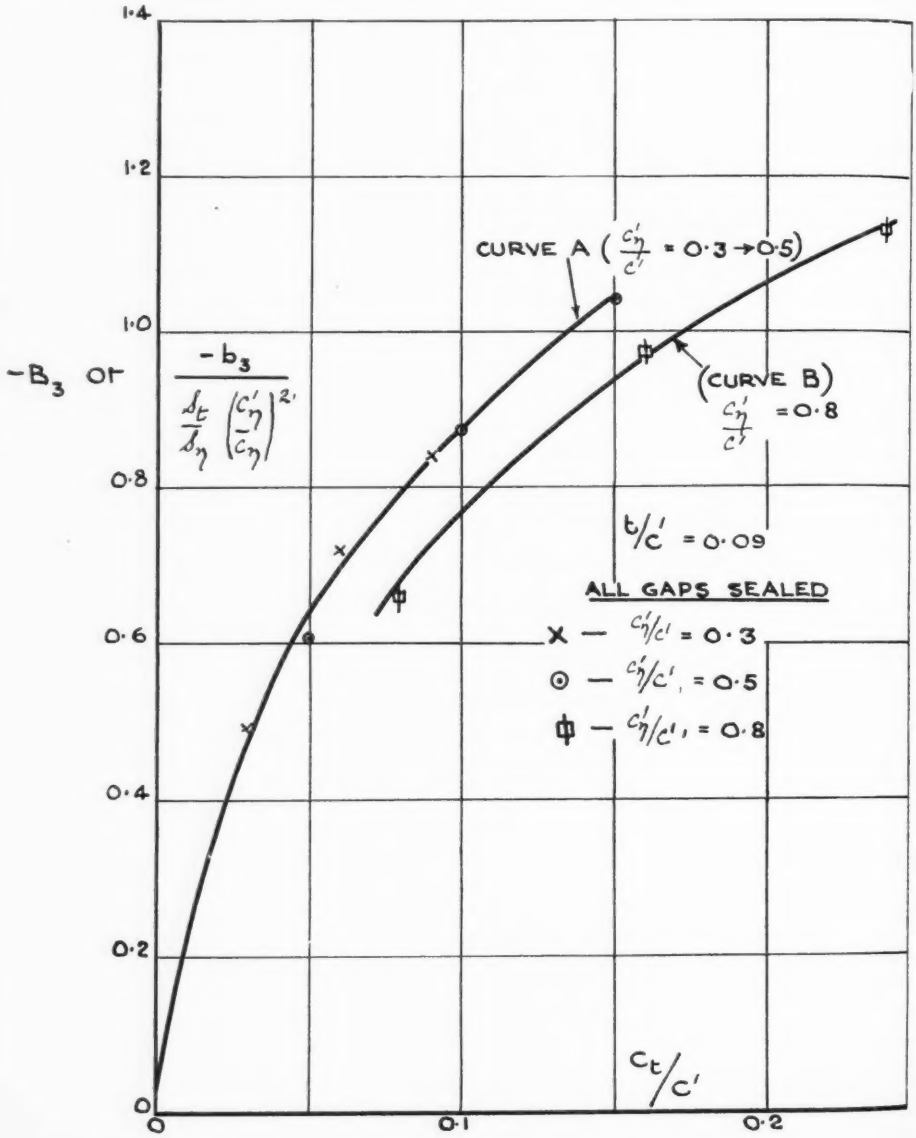


Fig. 30.
Variation of B_3 with tab chord/total chord for t/c — = 0.09.

12.3. *Upfloating Moment*

b_o, the upfloating moment is a function mainly of the camber of the section. Thin aerofoil theory can be used to estimate this quantity, but usually gives an overestimate.

12.4. *Control Balance*

In general the effects of control balance have been expressed in the form of increments Δb_1 and Δb_2; this is convenient for design purposes. Analyses to date cover the following types of balance:—

1. Westland-Irving.
2. Set Back Hinge Balance.
3. Horn Balance.

The analysis of the first type of balance is not yet complete and so no results can be quoted.

The second type of balance has been dealt with in some recent unpublished work (see para. 8.2).

The curves necessary for the estimation of Δb_{1t} and Δb_{2t} are shown in Figs. 19-21. For a sealed control the balance decreases with increase in trailing edge angle according to the corrections

$\Delta b_1 = \Delta b_{1t}\,(1 - 4.9\,\tau^2)$

all nose shapes and

$\Delta b_2 = \Delta b_{2t}\,(1 - 10\,\tau^3)$

for circular nose shape

$= \Delta b_{2t}\,(1 - 4.3\,\tau^2)$

for elliptic nose shape.

The effect of unsealing the nose gap is, in general, to restore part of this loss, usually at the expense of an earlier stall.

The effect of horn balance can be summarised in the following expressions:—

For unshielded horns

$\Delta b_1 = AB^2\,(7.5 - 33.3\,t/c)$ (see Figs. 22, 23).

$\Delta b_2 = AB^2\,(6.5 - 30.7\,t/c)$

For shielded horns

$\Delta b_1 = AB^2\,(e^{x3} - 1)\,(4.36 - 19.4\,t/c)$

for round and elliptic noses.

$\Delta b_2 = AB^2\,(e^{x2} - 1)\,(3.78 - 17.9\,t/c)$

elliptic nose.

$= 1.29\,AB^2\,(e^{x2} - 1)\,(3.78 - 17.9\,t/c)$

round nose.

12.5. *Tab Hinge Moments*

(i) *About the Control Hinge*

Assuming linearity we have:—

$$C_H = b_o + b_1\alpha + b_2\eta + b_3\beta$$

The estimation of the quantity b_3 is covered by Lyons in his analysis of Ref. 15. Generally the tab may be assumed to remain effective up to 15° deflection. It can be shown that $b_3 \propto s_t/s_\eta$ and that increase in tab span is therefore more effective in increasing b_3 than increase of tab chord. (See Figs. 30, 31.)

(ii) *About its Own Hinge*

The hinge moment of the tab about its own hinge can be expressed as

$$C_{Ht} = c_o + c_1\alpha + c_2\eta + c_3\beta$$

The estimation of the quantities c_0, c_1, c_2 and c_3 is very unreliable. c_3 is the most important, and usually c_0 and c_1 are sufficiently small to be neglected. Rough expressions for the tab hinge moments (Ref. 17) are

$c_1 = c_2 = \frac{1}{4}\,c_3$

$c_3 = -(5\,c_t/c)$

(unbalanced tab).

$c_3 = -(5\,c_t/c)\,(1 - X/43)$

balanced tab with blunt nose.

$c_3 = -(5\,c_t/c)\,(1 - X/60)$

balanced tab with sharp nose,

$$\text{where } X = \frac{\text{area ahead of hinge}}{\text{area aft of hinge}}$$

12.6. *General*

This summarises the data so far collected together in a form convenient for design use. It may be emphasised here that a great deal

remains to be done before control design is a matter of calculation rather than one of experience and experiment; we are still a long way from a full understanding of the phenomena associated with control lift and hinge moments.

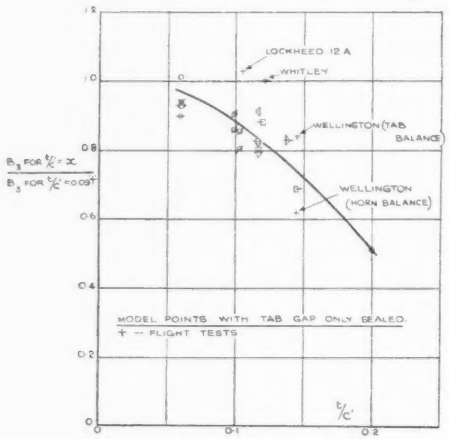


Fig. 31.

* Read off curve A in Fig. 30 for *all* gaps sealed. Variation of B_3 with thickness chord ratio.

Notation

Para. 6

x, y = the co-ordinates of points on the aerofoil with the system of axes shown in the figure of Appendix I.

V = the stream velocity.

C_H = the hinge moment of the control $= b_0 + b_1\alpha + b_2\eta$.

C_L = the lift coefficient of the aerofoil $= a_0 + a_1\alpha + a_2\eta$.

K = the ratio of the actual circulation to the Joukowski value.

h and U are as defined in Appendix II.

δ = the thickness of the boundary layer.

c = the aerofoil chord.

The suffix T denotes the theoretical value of the coefficient.

Para. 8.2

S_b = the area of the forward balance.

c_b = the chord of the forward balance (mean).

S_η = the area of the control aft of hinge.

c_η = the mean chord of the control aft of hinge.

$2t$ = the mean thickness of the aerofoil at the hinge.

Para. 8.3

A = the aspect ratio of the horn balance.

$B = \sqrt{\dfrac{S_b c_b}{S_\eta c_\eta}}$

t/c = the mean thickness chord ratio over the horn span.

Para. 8.4

E = the chord ratio of the control.

Para. 8.5

σ = the suction at any point x of the upper surface of the aerofoil.

p = the pressure at any point y of the lower surface of the aerofoil.

x and y are measured along the chord line of the aerofoil.

Para. 11

p_c = the pressure at any point of the aerofoil (compressible flow).

p_i = the pressure at any point of the aerofoil (incompressible flow).

M = the ratio of the velocity to that of sound.

Capitals are used for the purpose of differentiating between compressible and incompressible flow conditions.

Suffix o denotes two dimensional values.

$1/\beta$ the factor $1/\sqrt{(1-M^2)}$.

Para. 12.5

s_t = the span of the tab.

s_η = the span of the control surface.

c_t = the mean chord of the tab.

PART III

CONCLUDING REMARKS.

13. *Prototype Testing*

It must be apparent from the ground already covered that we have much to learn in detail about controls and their ways. In particular, while the existing body of theoretical and empirical knowledge now enables us to predict, often with reasonable accuracy, what will be the consequences of certain *changes* in the shapes and sizes of controls, an estimation of the *absolute* values of the various lift and hinge moment parameters from a knowledge of the geometrical proportions may well be considerably in error; large errors may also arise in interpreting the results of tunnel tests of a model of the control to be used, since the model itself may not represent with sufficient accuracy the precise shape of the control to be flown, while the boundary layer conditions in the tunnel may be unrepresentative of the usually unknown boundary layer conditions on the aircraft.

Such uncertainty in the absolute values of the relevant quantities adds greatly to the importance of prototype testing. When a prototype first flies, it is extremely unlikely that the control characteristics will be just what the designer expected; in particular the hinge moment characteristics are liable to be wildly out. It is during the early development flights of a prototype that much of the aerodynamic design of the control surfaces is often done, as shapes and sizes are altered in order to give the pilot what he wants. And it is at this stage that shrewd use of the information already gathered by research workers can save an immense amount of time.

In this connection early and comprehensive instrumentation of the prototype is essential. Unless the characteristics of the unsatisfactory controls are established quantitatively, the development engineer has no datum from which to work. Once the numbers have been obtained, existing knowledge can be rationally applied to guide him as to the changes needed to put the controls right.

We come here to a second important point. It is obviously wise for the designer to anticipate such changes, so far as is possible, when the type is on the drawing board; and to make provision on the prototype aircraft for these changes to be done quickly. Typical examples are mounting the hinge bearings of the control surface in slides, with screw adjustment, so that fore-and-aft hinge position can be altered, thereby enabling percentage balance to be adjusted; providing a geared tab with a wide range of alternative gearings; making the Frise nose detachable and building several sets, possible in wood, of different shapes, and so on. From this viewpoint the spring tab is one of the most useful devices, since a wide range of alternative springs and alternative tab leverages can be provided, giving the development engineer power to alter the overall hinge moment characteristics within very wide limits to allow for any errors in the estimation of basic control heaviness.

14. *Instrumentation*

The importance of early and comprehensive instrumentation of the prototype has been mentioned. It must be stressed, however, that the automatic observer box is not in any sense a substitute for a good test pilot; it is merely a necessary adjunct whose main purpose is to tell the engineer the technical reasons behind some of the pilot's likes and dislikes. Neither does use of an automatic observer allow the employment of a less highly trained flight technician—unless the records are examined intelligently they are of little value. A highly skilled test pilot and a first class technician, with limited instrumental equipment, who think carefully over what tests should be done, and which quantities should be measured and which neglected, form a team far more valuable to a designer than an indifferent pilot and

second-rate technician equipped with an unlimited number of expensive instruments.

15. *Training of the Flight Test Team*

In considering the team of test pilots and technicians concerned with the development of a prototype, two points may be made. Firstly it is very valuable if the test pilot has obtained a technical background, however limited, on stability and control matters. When trying to get one's ideas straight on a knotty handling point, unadulterated common sense may lead to very misleading conclusions; common sense combined with a limited but sound knowledge of technicalities can produce useful results. In this connection the Empire Test Pilots' School at Boscombe Down is a big step in the right direction. The second point to be made concerns the flight technician. His value is undoubtedly enhanced if he is given the opportunity of getting experience as a pilot —again only limited experience is needed on comparatively tame types. Unless a man has had such solo experience, obtaining thereby at first hand an appreciation of the difficulties of the flying business, he will lack a full appreciation and understanding of many of the more subtle points raised by the test pilot. Any trouble or expense incurred by a firm in giving the flight technician such flying training will be amply repaid.

16. *The Value of Numerical Standards*

When experience has shown the desirability of insisting upon some particular form of handling characteristic in future designs, either in the interests of safety or operational utility, the normal procedure is for some form of requirement to be hammered out by joint consultation between representatives of the Industry and of the Official side. As such requirements grow in number, they form a sort of handling schedule which guides the team engaged on prototype development as to the minimum standards which must be reached.

Some progress has steadily been achieved in making such standards quantitative rather than qualitative. The authors would like to stress the importance of putting in the numbers. In the past there has been a tendency for handling requirements to be liberally sprinkled with phrases of the type " the change of trim shall not be excessive," " stick and pedal loads to do this shall be reasonable," " no undue tendency to swing," and so on. Although qualitative statements of this sort often sound eminently sensible, they can lead to much confusion in interpretation, since opinions are bound to differ on the precise shade of meaning to be given to " excessive," " unduly large," " reasonable." and the rest, in terms of numerical values. It seems far better to insert definite figures whenever possible for tolerable ranges of pilots effort (when dealing with trim change), stick force per " g," stability margins, rate of roll, etc., even if at first some of the numbers may be based on rather tenuous evidence. They can always be modified as experience dictates. With increasing use of instruments quantitative information on good and bad aeroplanes should accumulate more rapidly than in the past. By using such experience it should be possible to develop progressively a comprehensive handling schedule, of a distinctly quantitative character, which so far as possible epitomises our experience of what is and what is not acceptable to the average pilot. Such a schedule would be of very real assistance during prototype development.

17. *Acknowledgments*

We would like to thank the experimental test pilots at Farnborough, our colleagues on the staff of the Royal Aircraft Establishment, and the staff of the National Physical Laboratory, for assistance given during numerous discussions on the topics dealt with

in this paper. In particular we would like to pay tribute to Mr. S. B. Gates, to whom for many years the authors have both been deeply in debt for patient guidance through the tangled but fascinating highways and byways of stability and control research.

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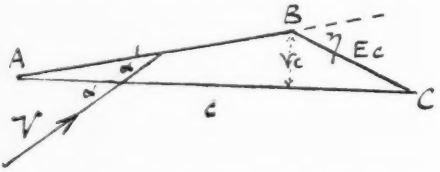
Appendix I

Thin Aerofoil Theory for a Flapped Aerofoil



Let the aerofoil be represented by the line ABC and the various chords, angles, etc., be as marked. Then AC is chosen as the axis of x and the normal at A as the y axis. We shall now introduce a new parameter defined by

$$x = \tfrac{1}{2}c\,(1-\cos\theta) \qquad . \qquad (1)$$

It is further assumed that the vorticity at any point of the aerofoil can be written

$$k = 2V\,\{\,A_0 \cot \tfrac{1}{2}\theta + \sum_1^{\infty} A_n \sin n\theta\,\} \qquad (2)$$

or

$$k\,dx = cV\,\{\,A_0\,(\cos\theta+1) + \sum_1^{\infty} A_n \sin n\theta \sin\theta\,\}\,d\theta$$

From which it follows that the lift force is

$$L = \int_0^c \rho V k\,dx = \pi c \rho V^2\,(A_0 + \tfrac{1}{2}A_1) \qquad . \qquad (3)$$

or in coefficient form

$$C_L = 2\pi\,(A_0 + \tfrac{1}{2}A_1) \qquad . \qquad (3a)$$

The pitching moment about the leading edge is

$$M = -\int_0^c \rho V k x\,dx = -(\pi/4)\,c^2 \rho V^2\,(A_0 + A_1 - \tfrac{1}{2}A_2) \qquad (4)$$

or in coefficient form

$$C_m = -(\pi/2)\,(A_0 + A_1 - \tfrac{1}{2}A_2) \qquad (4a)$$

$$= (\pi/4)\,(A_2 - A_1) - \tfrac{1}{4}C_L \qquad . \qquad (4b)$$

The direction of the resultant velocity adjacent to the aerofoil must be parallel to the surface and so at each point of the aerofoil

$$\alpha + v/V = dy/dx \qquad . \qquad (5)$$

where v is the induced velocity.

This gives

$$dy/dx = \alpha - A_0 + \sum_1^{\infty} A_n \cos n\theta$$

[see p. 90, Ref. 2] and so

$$\alpha - A_0 = (1/\pi)\int_0^{\pi} dy/dx\,d\theta \qquad . \qquad (6)$$

$$A_n = (2/\pi)\int_0^{\pi} dy/dx \cos n\theta d\theta \qquad (7)$$

These are general expressions and can be used to obtain lift, pitching moment, or h_0 for any thin aerofoil.

In the case of a symmetrical aerofoil the shape is defined by (see figure)

$$\left.\begin{aligned} dy/dx &= \gamma/(1-E),\ 0<\theta<\phi \\ dy/dx &= -\gamma/E,\ \phi<\theta<\pi \end{aligned}\right\} \qquad (8)$$

where

$\theta = \phi$ defines the point B.

So that

$$\cos\phi = -(1-2E) \qquad . \qquad (9)$$

Now

$$\left.\begin{aligned} \alpha' &= \alpha - \gamma/(1-E) \\ \text{and} \qquad \eta &= \gamma/E + \gamma/(1-E) \end{aligned}\right\} \qquad . \qquad (10)$$

From equations **6**, **7**, **8**, **10**, we have

$$\left.\begin{aligned} A_0 &= \alpha' + \{\,(\pi-\phi)/\pi\,\}\,\eta \\ A_n &= (2\sin n\phi/n\pi)\,\eta \end{aligned}\right\} \qquad . \qquad (11)$$

From 3*a*

$$C_L = 2\pi\,\{\,\alpha' + [\,(\pi-\phi)/\pi\,]\,\eta + (\sin\phi/\pi)\,\eta\,\}$$

which by comparison with

$$C_L = a_1\alpha' + a_2\eta$$

gives

$$\left.\begin{aligned} a_1 &= 2\pi \\ a_2/a_1 &= (\pi-\phi)/\pi + \sin\phi/\pi \end{aligned}\right\} \qquad (12)$$

Hinge Moments

Since the lift force on an element dx of

the aerofoil chord is $\rho vkdx$ the hinge moment is

$$H = -\int_B^C \rho Vk \{ \alpha - (1-E)\, c \}\, dx$$

or

$$H = -\tfrac{1}{2}\rho V^2 c^2 \int_\phi^\pi \{ A_0 (1+\cos\theta) + \sum_1^\infty A_n \sin n\theta \sin\theta \} (\cos\phi - \cos\theta)\, d\theta$$

But we can write

$$C_H = \frac{H}{(\frac{1}{2}\rho V^2 E^2 c^2)} = b_1\alpha' + b_2\eta \qquad (14)$$

so that

$$-4E^2 (b_1\alpha' + b_2\eta) = 2\cos\phi \int_\phi^\pi [A_0 (1+\cos\theta) + \sum_1^\infty A_n \{ \cos n-1\theta - \cos n+1\theta \}]\, d\theta$$

$$- \int_\phi^\pi [2A_0 (1 + 2\cos\theta + \cos 2\theta) + \sum_1^\infty A_n \{ \cos n-2\theta - \cos n+2\theta \}]\, d\theta$$

On integration let C_n be the coefficient of A_n.

Then in general for $n > 2$

$$C_n = 2\cos\phi \left\{ \frac{\sin (n+1)\phi}{n+1} - \frac{\sin (n-1)\phi}{n-1} \right\} - \left\{ \frac{\sin (n+2)\phi}{n+2} - \frac{\sin (n-2)\phi}{n-2} \right\}$$

For $n \leqslant 2$

$$C_2 = 2\cos\phi \left\{ \frac{\sin 3\phi}{3} - \sin\phi \right\} - \left\{ \frac{\sin 4\phi}{4} + (\pi - \phi) \right\}$$

$$C_1 = 2\cos\phi \left\{ \frac{\sin 2\phi}{2} + (\pi - \phi) \right\} - \left\{ \frac{\sin 3\phi}{3} - \sin\phi \right\}$$

$$C_0 = 4\cos\phi \{ (\pi - \phi) - \sin\phi \} - 2 \{ (\pi - \phi) - 2\sin\phi - \tfrac{1}{2}\sin 2\phi \}$$

Thus

$$-4E^2 (b_1\alpha' + b_2\eta) = \sum_0^\infty C_n A_n \qquad (16)$$

Using equations (11) we have

$$-4E^2 b_1 = C_0 \qquad (17)$$

$$-4\pi E^2 b_2 = (\pi - \phi)\, C_0 + 2\sum_1^\infty \frac{\sin n\phi}{n} C_n \qquad (18)$$

The general term of this expression ($n > 2$) is

$$\frac{2\sin n\phi}{n}{}_n = 4\cos\phi \left\{ \frac{\sin n+1\phi \sin n\phi}{n(n-1)} - \frac{\sin n\phi \sin (n-1)\phi}{n(n-1)} \right\} - 2 \left\{ \frac{\sin n-2\phi \sin n\phi}{n(n+2)} - \frac{\sin n\phi \sin (n-2)\phi}{n(n-2)} \right\}$$

The summation of each bracket can be easily performed giving

$$-4E^2\pi b_2 = (\pi - \phi)\, C_0 + 4(\pi - \phi)\sin\phi\cos\phi - (\pi - \phi)\sin 2\phi + 2\sin^2\phi \qquad (19)$$

From 17 and 19 we have

$$\left.\begin{aligned} -4E^2 b_1 &= 2(\pi - \phi)(2\cos\phi - 1) - \sin 2\phi + 4\sin\phi \\ \text{and} \\ -4\pi E^2 b_2 &= 2(\pi - \phi)^2 (2\cos\phi - 1) + 4(\pi - \phi)\sin\phi + 2\sin^2\phi \end{aligned}\right\} \qquad (20)$$

Pitching Moment

This follows readily from equations 11 and 4*b*, thus

$$C_m = \frac{\pi}{2}\left(\frac{\sin 2\phi}{2\pi} - \frac{\sin\phi}{\pi} \right)\eta - \tfrac{1}{4}C_L = \frac{\sin\phi}{2}(\cos\phi - 1)\,\eta - \tfrac{1}{4}C_L \qquad (21)$$

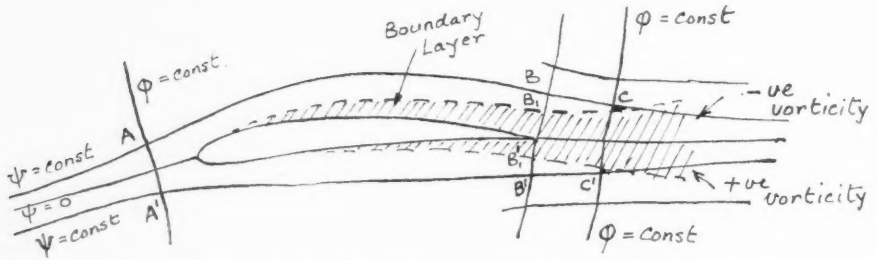
Appendix II

Proof of Taylor's Theorem on the Vorticity Passing into the Wake

Let $\psi = \text{const.}$ in figure represent the average streamlines of the flow past the aerofoil; these together with their normals, $\phi = \text{const.}$, define a curvilinear system of co-ordinates.

Denote the distance along the streamlines, $\psi = \text{const.}$ by "s" and that along the normals, $\phi = \text{const.}$ by "n." Then the velocity at any point is

$$q = \frac{\partial\psi}{\partial n}$$



which outside the boundary layer and wake becomes,

$$h = \frac{\partial \psi}{\partial n}$$

where h is the velocity of the flow in the irrotational field which exists in this region by definition. An analogous function is defined by

$$h_1 = \frac{\partial \phi}{\partial s}$$

and outside the boundary layer and wake

$$h = \frac{\partial \phi}{\partial s}$$

Consider the circulation k_1 in the path $ABB'A'A$ composed of the streamlines AB, $B'A'$ and the normal $\phi = \text{const.}$ through the trailing edge, and another normal forward of the leading edge.

We have

$$k_1 = \int_A^B h\,ds - \int_{A'}^{B'} h\,ds$$
$$= \phi_B - \phi_{B'}$$

Similarly for the path $ACC'A'A$.

$$k_2 = \phi_C - \phi_{C'}$$

So that

$$k_2 - k_1 = (\phi_C - \phi_B) - (\phi_{C'} - \phi_{B'}) = 0$$

Since B, B' and C, C' lie on two ϕ lines differing by the same constant.

Hence the circulation in the paths which enclose the aerofoil and its boundary layer, and pass normally to the streamlines in the wake is constant. Also the net vorticity enclosed in sections of the wake such as $CB_1B_1'C'C$, is zero.

Thus equal amounts of positive and negative vorticity pass into the wake at the trailing edge.

Howarth's approximation to this condition easily follows, since the vorticity at any point is given approximately by

$$\zeta = -\partial q / \partial n$$

and the rate at which it is carried past any section of the boundary layer is

$$-\int_0^U q\,(dq/du)\,du = -\tfrac{1}{2}U^2$$

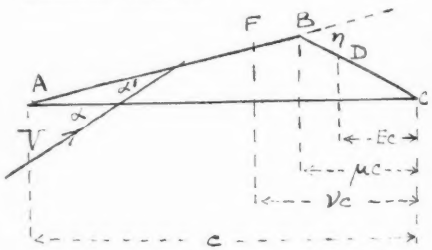
where U is the velocity at the edge of the boundary layer.

Hence by Taylor's theorem,

$$U_u^2/U_1^2 = 1.0$$

Appendix III.

Thin Aerofoil Theory for Set Back Hinge Balanced Controls



F is nose. B position of pressure peak. D hinge.

Let $AFBDC$ represent the aerofoil with set-back hinge balanced flap and the notation as in figure.

Take the origin of co-ordinates at A, the axis of x along the base line AC, and the y axis normal to it.

As in Appendix I we write

$$x = \tfrac{1}{2}c\,(1 - \cos\theta)$$

$$\left.\begin{array}{ll} \text{At } A & \theta = 0,\ \cos\theta = 1 \\ \text{At } F & \theta = \chi,\ \cos\chi = -(1-2\nu) \\ \text{At } B & \theta = \psi,\ \cos\psi = -(1-2\mu) \\ \text{At } D & \theta = \phi,\ \cos\phi = -(1-2E) \end{array}\right\} \quad (1)$$

The aerofoil shape is defined by

$$\left.\begin{array}{l} 0<\theta<\psi;\ dy/dx=\gamma/(1-\mu) \\ \psi<\theta<\pi;\ dy/dx=-\gamma/\mu \end{array}\right\} \quad (2)$$

Also, see figure,

$$\left.\begin{array}{l} \alpha'=\alpha-\gamma/(1-\mu) \\ \eta=\gamma/\mu+\gamma/(1-\mu) \end{array}\right\} \quad . \quad (3)$$

Assuming a distribution of vorticity along the aerofoil in the form of the series

$$kdx=cV\left\{A_0(1+\cos\theta)+\sum_1^{\infty}A_n\sin n\theta\sin\theta\right\}d\theta \quad . \quad (4)$$

then it follows that (see Appendix I)

$$\left.\begin{array}{l} \alpha-A_0=(1/\pi)\int_0^{\pi}(dy/dx)\,d\theta \\ A_n=(2/\pi)\int_0^{\pi}(dy/dx)\cos n\theta d\theta \end{array}\right\} \quad (5)$$

As in Appendix I, putting ψ for ϕ,

$$\left.\begin{array}{l} A_0=\alpha'+\{(\pi-\psi)/\pi\}\eta \\ A_n=\{(2\sin n\psi)/(n\pi)\}\eta \end{array}\right\} \quad (6)$$

Since

$$C_L=2\pi(A_0+\tfrac{1}{2}A_1)$$

it follows that

$$\left.\begin{array}{l} a_1=2\pi \\ a_2/a_1=(\pi-\psi)/\pi+(\sin\psi)/\pi \end{array}\right\} \quad (7)$$

As $\psi\to\phi$ these reduce to equations (12) of Appendix I.

Hinge Moments

Since the lift on an element dx of the aerofoil chord is $\rho Vkdx$ the hinge moment is

$$H=-\int_F^C\rho Vk\{x-(1-E)c\}\,dx$$

The integrand is discontinuous at the point B, but H possesses a limiting value.

Proceeding as in Appendix I, we have

$$-4E^2(b_1\alpha'+b_2\eta)=\sum_0^{\infty}C_nA_n \quad (8)$$

Thus

$$\begin{array}{l} -4E^2b_1=4\cos\phi\{(\pi-\psi)-\sin\chi\} \\ \quad -2\{(\pi-\chi)-2\sin\chi-\tfrac{1}{2}\sin 2\chi\} \end{array} \quad (9)$$

Also

$$\begin{array}{l} -4\pi E^2b_2=C_0(\pi-\psi)+2\sin\psi C_1+\sin 2\psi C_2 \\ \quad +2\sum_2^{\infty}\{(\sin n\psi)/n\}C_n \quad . \end{array} \quad (10)$$

The summations are more difficult in this case.

Finally, however, letting

$$\Phi=\tfrac{1}{2}(\psi-\chi)$$

and

$$\Psi=\tfrac{1}{2}(\psi+\chi)$$

we have

$$\begin{array}{l} -4\pi E^2b_2=(\pi-\psi)\left\{4\cos\phi(\pi-\chi-\sin\chi)\right. \\ \qquad \left.-2\left(\pi-\chi-2\sin\chi-\dfrac{\sin 2\chi}{2}\right)\right\} \\ \quad +2\sin\psi\left\{\left(\dfrac{\sin 2\chi}{2}+\pi-\chi\right)2\cos\phi\right. \\ \qquad \left.-\left(\dfrac{\sin 3\chi}{3}-\sin\chi\right)\right\} \\ \quad +\sin 2\psi\left\{2\cos\phi\left(\dfrac{\sin 3\chi}{3}-\sin\chi\right)\right. \\ \qquad \left.-\left(\dfrac{\sin 4\chi}{4}+\pi-\chi\right)\right\} \\ \quad +4\cos\phi\left\{\dfrac{\sin\Psi\sin 7\Phi}{3}\right. \\ \qquad \left.-\dfrac{\sin 3\psi\sin 2\chi}{6}-\dfrac{\sin\Phi\sin 7\Psi}{3}\right\} \\ \quad +16\cos\phi\sin\Phi\sin\Psi\left\{\tfrac{1}{2}\log\left(\dfrac{\sin\Psi}{\sin\Phi}\right)\right. \\ \qquad \left.-\sum_{r=1}^{3}\dfrac{\sin r\psi\sin r\chi}{r}\right\} \\ \quad -2\left\{\sin 2\Psi\left(\dfrac{\sin 8\Phi}{6}+\dfrac{\sin 10\Phi}{8}\right)\right. \\ \qquad \left.-\sin 2\Phi\left(\dfrac{\sin 8\Psi}{6}+\dfrac{\sin 10\Psi}{8}\right)\right\} \\ \quad +2\left\{\dfrac{\sin 3\psi\sin\chi}{3}+\dfrac{\sin 4\psi\sin 2\chi}{8}\right\} \\ \quad +2\sin 2\Psi\sin 2\Phi\left\{\tfrac{1}{2}\log\left(\dfrac{\sin\Psi}{\sin\Phi}\right)\right. \\ \qquad \left.-\sum_{r=1}^{4}\dfrac{\sin r\psi\sin r\chi}{r}\right\} \quad . \end{array} \quad (11)$$

Equations (9) and (11) combined with the corresponding equations of Appendix I will give the increments Δb_1 and Δb_2 due to the balance.

Appendix IV.

Spring Tab Theory

Consider control and tab both displaced downwards (*i.e.*, in the positive sense).

The hinge moments are:—

Control,

$$H = cSq\ (b_o + b_1\alpha' + b_2\xi + b_3\beta)$$

Tab,

$$H_t = c_tS_tq\ (c_o + c_1\alpha' + c_2\xi + c_3\beta)$$

Let

k_1 = gearing between stick and spring member.

k_2 = gearing between spring member and tab.

Suppose also that P_o is the preload, λ = the spring rate, and the co-ordinate defining the spring deformation is θ, then on the ground

$$P = P_o + k_1\lambda\theta$$
$$\beta = k_2\theta$$

In flight the pilot's force P is given by

$$P = P_o + k_1\lambda\theta - k_1k_2c_tS_tq\ (c_o + c_1\alpha' + c_2\xi + c_3\beta)$$

also

$$\beta = k_2\theta$$

Further we can write

$$P = mcSq\ (b_o + b_1\alpha' + b_2\xi + b_3\beta)$$

where m = stick gearing, tabs locked.

Then writing

$$K_1 = k_1/k_2 \text{ and } K_2 = k_1k_2 \cdot c_tS_t$$

we have

$$P = P_o + K_1\lambda\beta - K_2q\ (c_o + c_1\alpha' + c_2\xi + c_3\beta)$$

Eliminating β gives the pilot's stick force with the tab in operation.

Thus

$$P = P_o - K_2q\ (c_o + c_1\alpha' + c_2\xi) + \frac{(K_1\lambda - K_2qc_3)}{b_3} \cdot \frac{(P - P_L)}{mcSq}$$

where P_L (stick force, tab locked) $= mcSq\ (b_o + b_1\alpha' + b_2\xi)$

So that

$$P = P_o + (P_L - P_o) \left\{ 1 - \frac{1}{1 - \frac{K_1\lambda}{b_3}\frac{1}{mcSq} + \frac{K_2}{mcS}\frac{c_3}{b_3}} \right\} \frac{K_2q\ (c_o + c_1\alpha' + c_2\xi)}{1 - \frac{K_1\lambda}{b_3}\cdot\frac{1}{mcSq} + \frac{K_2}{mcS}\cdot\frac{c_3}{b_3}}$$

This is the general formula for the stick force. In practice the last term is usually neglected as c_o, c_1 and c_2 are very small.

Application of this general theory to particular designs is considered in Ref. 17 where the effect of the spring tab on stability is also discussed.

Appendix V.

Differential Gearing Theory

We shall use the suffices u and d to denote the up-going and down-going ailerons respectively. Then if m_u and m_d are corresponding gearings these are related to the stick displacement (x) thus

$$m_u = d\xi_u/dx \text{ and } m_d = d\xi_d/dx$$

If C_{Hu}, C_{Hd} be respectively the hinge coefficients of the up and down going ailerons, the pilot's force P is given by the equation of virtual work

$$Pdx = (C_{Hu}d\xi_u - C_{Hd}d\xi_d)\ \tfrac{1}{2}\rho V^2\tfrac{1}{2}S_\xi c_\xi$$

or

$$P/(\tfrac{1}{2}\rho V^2S_\xi c_\xi) = \tfrac{1}{2}\ (C_{Hu}m_u - C_{Hd}m_d)$$

Assume the hinge moment for a single aileron is

$$C_H = b_o + b_1\alpha + b_2\xi$$

Then if $\Delta\alpha$ is the incidence change due to response we have

$$C_{Hu} = b_o + b_1\ (\alpha + \Delta\alpha) — b_2\xi_u$$

and

$$C_{Hd} = b_o + b_1\ (\alpha - \Delta\alpha) + b_2\xi_d$$

It is easily shown that

$$\Delta\alpha = (\gamma\lambda l_\xi/lp)\ \tfrac{1}{2}\ (\xi_u + \xi_d) = (\gamma\lambda l_\xi/lp)\ \xi$$

where

$$\xi = \tfrac{1}{2}\ (\xi_u + \xi_d) = \text{mean angle.}$$

The up floating angle of the aileron at incidence α is given by

$$b_2\xi_f = b_o + b_1\alpha$$

Then if we write

$$(\lambda l_\xi/lp)\ y = n$$

we have,

$$C_{Hu} = -b_2\ (\xi_u - \xi_f) + nb_1 \cdot \xi$$

and

$$C_{Hd} = b_2\ (\xi_d + \xi_f) - nb_1 \cdot \xi$$

And so we have,

$$P/(\tfrac{1}{2}\rho V^2S_\xi c_\xi) = \tfrac{1}{2}\ b_2\ \{\ \xi_u m_u + \xi_d m_d - \xi_f\ (m_u - m_d)\ \} - nb_1\xi\ (m_u + m_d)$$

This may be written as

$$P/(\tfrac{1}{2}\rho V^2S_\xi c_\xi) = b_2\ (mk\xi - \delta\ .\ \xi_f - \epsilon)$$

where

$\xi = \frac{1}{2}(\xi_u + \xi_d)$ = the mean of the aileron angles.

$m = \frac{1}{2}(m_u + m_d)$ = the mean of the gearings.

$\epsilon = \frac{1}{2}(\xi_u - \xi_d)$

$\delta = \frac{1}{2}(m_u - m_d)$

and

$k = 1 - n\,(b_1/b_2)$ = the response factor.

Appendix VI.

Response of an Aircraft to Application of Aileron

Following Gandy, Ref. 31, and in the notation of R. and M. 1,801, the lateral equations of motion, with application of rolling moment C_l and yawing moment C_n, are

$$(D - y_v)(\mu v/V) + \mu(r\mu s/V) - \mu k\phi = 0$$
$$-(l_v/i_A)(\mu v/V) + (D - l_p/i_A)(\mu ps/V) - \left\{\left(\frac{E}{A}\right)D + \frac{l_r}{i_A}\right\}(\mu rs/V) = \mu C_l/i_A$$
$$-(n_v/i_c)(\mu v/V) - (ED/C + n_p/i_c)(\mu ps/V) + (D - n_r/i_c)(\mu rs/V) = \mu C_n/i_c$$
$$-\mu ps/V + D\phi = 0$$

where

$D = d/d\tau$, $\tau = (S\rho V/m)\,t$ and C_l, C_n are given as functions of τ according to the amount and rate of application of the controls.

Put C_l = const. and $C_n = 0$.

The determinant formed by coefficients on the left hand side is

$$F(D) = \begin{vmatrix} D - y_v & 0 & \mu & -\mu k \\ -l_v/i_A & D - l_p/i_A & -ED/A & 0 \\ -n_v/i_c & -ED/C - n_p/i_c & D - n_r/i_c & 0 \\ 0 & -1 & 0 & D \end{vmatrix}$$
$$= D^4 + B_2D^3 + C_2D^2 + D_2D + E_2$$

so that

$$F'(D) = 4D^3 + 3B_2D^2 + 2C_2D + D_2$$

Then the operational expression for $\mu ps/V$ is

$$\frac{\mu ps}{V} = 1/F(D) \begin{vmatrix} D - y_v & \mu & -\mu k \\ -n_v/i_c & D - n_r/i_c & 0 \\ 0 & 0 & D \end{vmatrix} \mu\,(C_l/i_A)$$

or

$$(ps/V)\,(i_A/C_l) = \frac{D^3 - \left(y_v + \frac{n_r}{i_c}\right)D^2 + \left(\mu\frac{n_v}{i_c} + y_v\frac{n_r}{i_c}\right)D}{F(D)}$$

This leads to the expression

$$(ps/V)\,(i_A/C_l) = X_1e^{z_1\tau} + X_2e^{z_2\tau} + X_3e^{a\tau}\sin b\tau + X_4e^{a\tau}\cos b\tau$$

Now the value of z_1 is large and negative, so that the first term diminishes rapidly with τ.

Thus an approximation to the average rate of roll achieved is given by the second term.

Performing the operations $D/F(D).1$, $D^2/F(D).1$, and $D^3/F(D).1$ in the above equation shows that

$$X_2 = \frac{z_2^2 - \left(y_v + \frac{n_r}{i_c}\right)z_2 + \left(\mu\frac{n_v}{i_c} + y_v\frac{n_r}{i_c}\right)}{F'(z_2)}$$
$$\fallingdotseq \mu n_v/i_cF'(z_2) \text{ since } z_2 \text{ and } y_v \ll \mu$$
$$\fallingdotseq \mu n_v/i_cD_2$$

It can be shown that approximately

$$D_2 = \mu\frac{n_v}{i_c} - l_p/i_A - \frac{l_v}{i_A}\frac{i_c}{n_v}\left(k - \frac{n_p}{i_c}\right)$$

Giving

$$X_2 = \frac{1}{-\frac{l_p}{i_A} - \frac{l_v}{i_A}\frac{i_c}{n_v}\left(k - \frac{n_p}{i_c}\right)}$$

The second equation of motion reduces, if v and r are neglected, to

$$(D - l_p/i_A)(\mu ps/V) = \mu C_l/i_A$$

For instantaneous application of C_l the solution is

$$(ps/V)\,(i_A/C_l) = -(i_A/l_p)\left(1 - e^{\frac{l_p}{i_A}\tau}\right)$$

$$\text{Lim } \tau \to \infty\ (ps/V)\,(i_A/C_l) = -i_A/l_p$$

If the ratio of the average of $ps/V \cdot i_A/C_l$ to this limit is λ then from equation for X_2

$$\lambda = \frac{1}{1 + \frac{l_v}{l_p}\frac{i_c}{n_v}\left(k - \frac{n_p}{i_c}\right)}$$

Thus an approximation to the response equation is

$$(ps/V)\,l_p + \lambda C_l = 0 \text{ (see Fig. 39).}$$

Let the starboard aileron angle be $+\xi$ and the port aileron angle be $-\xi$..

Then $C_l = -l\xi \cdot \xi$.

If ys is the distance of the mid-span of the aileron from the plane of symmetry the change of incidence $\Delta\alpha$ over the starboard aileron

$$= -pys/V = -(\lambda y l_\xi / l_p)\,\xi = -n\xi.$$

Then

$$C_{Hd} = b_0 + b_1(\alpha - n\xi) + b_2\xi$$
$$C_{Hu} = b_0 + b_1(\alpha + n\xi) - b_2\xi$$

where u, d denote up-going and down-going aileron respectively.

Thus the hinge moment to be balanced by the pilot's effort is

$$C_H = C_{Hd} - C_{Hu} = (b_2 - nb_1)\,\xi$$

(based now on total aileron area)

$$= kb_2 \cdot \xi$$

where

$$k = 1 - n(b_1/b_2),$$

the response factor. The equation of virtual work gives the pilot's force

$$P = mS_\xi c_\xi \tfrac{1}{2}\rho V^2 C_H$$
$$= \tfrac{1}{2}\rho V^2 m S_\xi c_\xi k b_2 \xi$$

Substituting for ξ in terms of the rate of roll, we have

$$P = \tfrac{1}{2}\rho V^2 m S_\xi c_\xi\,(kb_2/l_\xi)\,(l_p/\lambda)\,(ps/V)$$

In this form the theory of aileron performance was developed by Gates and Irving in Ref. 23.

DISCUSSION

SIR MELVILL JONES (Chairman, A.R.C.: Fellow): He congratulated the authors on the form of the paper and on its presentation, and said they had provided a really magnificent example of exposition. Having tried to lecture on the subject from time to time, he appreciated how very difficult it was to present it; the Society should be grateful to the authors for the manner in which they had presented their information.

A remark in the lecture which had impressed him particularly was that concerning the importance of test work on controls being carried out by pilots possessing technical knowledge, and of research work on controls being carried out by technicians having practical flying experience, even though that experience might be confined only to easy types of aircraft. It was difficult to overemphasise the importance of this if the work was to be kept on practical lines. The subject was one in which it was easy to wander off into elaborate mathematics; and in doing so to forget that one was trying to produce an aeroplane which the pilot liked and could handle.

Another remark by the authors which had impressed him particularly was that concerning the importance of obtaining quantitative data relating to control, so that specifications could be more precise and not have to contain vague statements such that some particular aspect of control must be "satisfactory." He had been so impressed with the need for more quantitative data on control that he had begun, shortly before the war, to get experiments going on this subject at Cambridge, but the war had intervened and the work had to be dropped. He was very glad to hear that the authors were making such good progress in this direction.

Having listened to lectures on the subject, and having seen a little of what was going on, Sir Melvill said it appeared to him that the control problem was tending to get out of hand when applied to very big and the very fast aircraft. In very big aircraft, or in very fast aircraft of moderate size, the forces on the control surfaces were becoming disproportionately large compared with the strength of a man. The authors of the paper and others, by their work, were putting off the day when we should have to use mechanical power on the controls, but even they could not put it off for ever. He believed that, within an unspecified number of years very considerable use would be made of mechanical power for the manipulation of the controls of our larger and faster aircraft. That did not mean necessarily that there was no need to continue with the kind of work that was being done nowadays, because the longer we could postpone the introduction of mechanical power for that purpose, the better. But it was vital that, in addition to the study of the controls them-

selves, the Government research departments and the Industry should be making a serious effort to develop power controls for use when they were required, and to give them a sufficient number of hundreds of hours of trial in the air, so that when it became necessary to use them they would be sufficiently reliable to justify their acceptance by aircraft operators without undue fear of failure.

Mr. D. L. ELLIS (Vickers-Armstrong Ltd.: Fellow): He supported the authors very strongly in their advocacy of instrumentation within reasonable limits, particularly now that spring tab controls were coming to the fore. Quoting a case in which instrumentation had proved to be very valuable, he said it happened that there were only two instruments available and they were put on spring tabs on the ailerons. After the first two flights it was realised that when the stick was in the neutral position the tabs were up by about half their travel. At first that had caused a great deal of consternation; but it was then realised that the tab was being pushed against the spring and that the ailerons were never at neutral. Although the pilots had said that it was the best control they had ever handled, it was in fact misbehaving atrociously. But for instrumentation, that aeroplane might have gone through life in that condition; but, having found out the facts by means of instruments, it was found possible to make suitable alterations which had increased the power of the ailerons by perhaps 50 per cent.

As a very strong advocate of spring tabs, he was sorely tempted to branch off into a discussion of their merits. In spite of Sir Melville Jones's remarks concerning power-operated controls, perhaps he might suggest using spring tabs on spring tabs for very big aeroplanes! However, that might be regarded as an attempt to carry the use of spring tabs to extremes.

In the discussion of limitations of size, Mr. Thomas had mentioned the possibilities of the aerodynamic booster, and had seemed rather to brush it aside without a great deal of consideration. Admittedly boosters were slightly complicated; but an aeroplane had been flown with a device which was in effect a negative booster, its purpose being to limit the travel of the control at high speeds. It was perfectly satisfactory, simple mechanically, and could not jam. There seemed no reason why such a device, turned the other way round, should not be used as a booster. We were still a long way from being driven to power-operated controls, except for considerations of weight. He asked if the authors had any ideas of the possible future developments of controls which would eliminate mass balance. An aeroplane which to-day was considered to be fairly large carried mass balance which was most easily measured, literally, in hundredweights; any development of control design which could reduce the amount of mass balance necessary would solve a very difficult problem, especially as most of the weight was right down at the tail end of the aeroplane, where it was most embarrassing. The only development he knew of was the spoiler control, instead of ailerons, for rolling.

Mr. N. E. ROWE (D.T.D., M.A.P.: Fellow): When the Lectures Committee of the Society had asked for a lecture on the subject of control surface design it had not really appreciated the difficulty of presenting the subject. But the authors had overcome the difficulty magnificently, and he congratulated them both very heartily. They had dealt with a most difficult subject within the compass of a comparatively short paper, and had given a very good survey of it.

One was interested, of course, in the results obtained on the aircraft. As he viewed the situation, never before had we been presented with such a tremendous wealth of data and information, and never before had we approached each problem so entirely *ad hoc* as in the case of controls. As Mr. Morgan had said, the designer never expected the controls to be right in the prototype; they were expected to be slightly out, and Mr.

Rowe suggested that as a rule they were wildly out. On the other hand, in view of the mass of data that was available, one was completely puzzled as to why we were in that state. There were different nose shapes and different balances and various means of getting towards what we required; we paid our money and took our choice, but there was never any guarantee that one's designs would be right. The R.A.E. was trying to put the matter right, and the work at the N.P.L. particularly was taking us a long way along the road.

But he was always puzzled as to why we could not expect more to come out of wind tunnel results; presumably it was a question of the scale effect and the difficulty of representing the various interferences in a scale model. Perhaps that is where our friends in America have an advantage over us, in being able to conduct model tests on a very much bigger scale. He asked whether we in this country could carry out larger scale tests than we had done in the past, particularly on balance problems.

A great deal of work had been devoted to the problem of harmony before the war, but it had since slid out of our ken because other matters were before us at the moment. Mr. Rowe felt very strongly, with Sir Melville Jones, that we should have to adopt power-operated controls; then we should look at the problem in quite a different way. Power-operated controls ought to be adopted sooner rather than later; the pilot's precise ideas of balance and harmony would not then enter into the matter to any degree. We tended to get ourselves into a very bad state in respect of large aircraft and very fast aircraft because of the " aeroelastic " and distortion effects which the authors had mentioned. Either we must develop controls which retained their precision at the high speeds of flight that would be attained, which was a structural and mechanical problem, or we must eliminate the " aeroelastic " and distortion effects by cutting out the aerodynamic qualities induced, and that would be done by power operation. We must bend our minds intensely to that problem and obtain a solution as soon as we could. He did not agree with Mr. Morgan that it was a defeatist policy; it might appear so to one who had specialised on the aerodynamic side, but it was in fact the exercise of ingenuity in another direction, and it was very important.

It was pleasing to hear the reference made to instrumentation and to the need for real team-work, and especially to hear the reference to "sensible" instrumentation. One of the dangers of the application of instruments to experimental work was the tendency to over-do it, by installing instruments to take all the readings that one could possibly get out of each flight, so obtaining such a mass of data that one was appalled by the task of analysing it and putting it to use. Instrumentation needed to be applied for the particular purpose that one had in mind at the moment; having obtained the data for that purpose, one could add more instruments as necessary, but always in an economical way.

There was no doubt that a great deal of our troubles had arisen from the fact that we had adhered to the camber changing controls for so long. One had heard of methods that could control the boundary layer by suction or blowing; he would like to hear what the authors had to say on the possibilities of that class of thing, because at high speed, if we could have the lifting surfaces unspoiled by any sort of flap, so much the better.

Finally, Mr. Rowe said it seemed that the authors' work had been related largely to the standards of control that were demanded in military aeroplanes. Did they consider that the same standards of control were required for civil aircraft, or could we design things for civil aircraft which, for the effort expended on them, would give a cleaner aerodynamic surface?

Dr. D. CAMERON (A. & A.E.: Fellow): Those who spent their time testing rather than designing aeroplanes sometimes became a little impatient with regard to the inadequacy

of the science of designing proper controls. When prototypes came for test, one found that they were not correct, and one wondered why that should be so. Therefore, it was very good for those concerned with testing to hear a lecture such as that by Mr. Morgan and Mr. Thomas, giving a reminder of all the difficulties which had to be faced in designing controls which really did work. Indeed, as the result of the lecture he had gained an impression of almost incredible difficulties; and he wondered whether, if we were faced anew with the task of moving a large surface through a large angle when travelling at a very high speed, we should really tackle it by means of very elaborate theoretical treatment, very elaborate wind tunnel tests and a lot of hard thought, or whether we should not go straight away to some form of power operation, not only for the fast and large aircraft, but for any aircraft where it was likely to give advantages in respect of repeatability. He did not know very much about the possible snags from the stability point of view; presumably we should throw away stick-free advantages, and so forth, and presumably we should also get into the difficulty that the pilot would be able to break the aeroplane very easily.

The problem of breaking aeroplanes could do with a little more thought. The authors had recommended certain limits to the forces which the pilot should be asked to exert; those forces were comparatively low, as, for instance, 30 lb. with one hand on the elevator and 40 lb. with two hands. If the aeroplane were so designed that the pilot could produce the most violent manœuvre that he wanted to produce by exerting a force of 30 lb., then clearly he would be able to break the aeroplane very easily. Dr. Cameron asked for the authors' views on the necessity or otherwise of fitting some positive device to prevent breakage of aeroplanes in that way.

It was rather surprising to hear Mr. Morgan suggest that harmony of control was relatively unimportant in these days, for it seemed that the acceptable range of forces for which one could design each individual control was rather wide. A pilot would hesitate to say that only a certain force to do a certain thing was acceptable; different pilots had different preferences. If each control were designed separately to a reasonable standard, it did not follow automatically that one would get a combination which would not lead to putting on more for one control than another in a turn, for example, resulting in undesirable skids.

Endorsing the authors' comments on the value of quantitative measurements in prototype testing, he said that at Boscombe Down those measurements had been found to be invaluable, not only in deciding what was wrong with an aircraft as first received, but what was more important perhaps, in tracing each step taken in effecting improvement. One could present a quantitative statement, indicating numerically the extent of each improvement effected.

Finally, he asked what was the likelihood of the designer being able to deal with trim changes, particularly changes of directional trim with speed and power, in the absence, of course, of contra-rotating propellors, and so forth. They were very unpleasant from the pilot's point of view, and represented one of the major difficulties on quite a number of current types.

Mr. F. W. PAGE (Hawker Aircraft Co.: Associate Fellow): Commenting on the enthusiasm which had been expressed for the spring tab, he urged that it was not a cure-all; the addition of a spring tab to an existing unsatisfactory control surface, with little or no alteration of the control surface proportions or balance, would not usually produce a satisfactory result. For example, if on a particular aircraft large aileron angles were required to give reasonable rate of roll, the simple addition of spring tabs and the modification of existing balance would not greatly improve matters. He felt it to be essential that the surfaces be designed at the outset for spring tabs, and suggested that many installa-

tions had suffered in the past because that was not done. Too large control angles or tab angles could lead to very unpleasant effects, such as tab stalling and oscillation. Other disadvantages associated with spring tabs were, of course, the additional mechanical complication and the appalling weight of mass balance. In general, with a spring tab control the weight of mass balance was rather greater than the entire weight of the control surfaces and the operating mechanism less the mass balance weight. That was a considerable price to pay; and in view of the fact that in some cases spring tabs could operate, or had been shown to operate, without mass balance, more investigation of the flutter aspect was required. He asked if the authors could suggest ways in which the enormous mass balance weights could be reduced in the future.

There were advantages to be gained, of course, in many cases. From the manufacturer's point of view probably the chief advantages were the repeatability for a given performance and, possibly just as important, the reduction of development time. In respect of some aircraft it had been found possible, by using spring tabs on some controls, to reduce the development time to the order of one-quarter of the time that was normally accepted as necessary. But in dealing with spring tabs it was essential to try out the proposed design first, not necessarily on the prototype for which it was envisaged, but on some other aircraft, if the development time were to be greatly reduced. Having done that, it was possible to apply a similar sort of design to the prototype and, merely by alteration of linkages and spring rates, to achieve the desired result very quickly.

In that connection, in order to be able to make a good shot at the proportions, and so on, required in the first place, he pleaded for more generalised data such as that which Mr. Morgan and his associates had been preparing recently, on the lines of Mr. Lyons' data, on the effect of flaps on aerofoils, and so on. More data was required also on hinge moments on tabs, and particularly forces on tabs and control surfaces. The force aspect might become very important, particularly with power-operated controls, because with the more stringent performance requirements that Mr. Morgan had put forward it was possible that there would be a very large crop of troubles with control surface failures due to inadequate strength, resulting primarily from the inadequacy of the stressing data available.

Finally, Mr. Page expressed agreement with Mr. Morgan's remarks on the importance of mechanical design; indeed, he felt that it was even more important than the aerodynamic design, and in regard to spring tabs it was undoubtedly extremely important. For that reason he urged strongly that the torsion bar scheme of operation was much to be preferred to the coil spring type, particularly as one of the great "selling points" of the spring tab was its repeatability; it was very difficult to ensure a repeatable spring rate when using a coil spring. Torsion bar operation was simpler. Further, it was far easier to avoid friction, it could be modified easily, and it was easier to avoid backlash.

Mr. R. M. CLARKSON (De Havilland Ltd.: Fellow): Discussing the spring tab and power boost, he said he had some revulsion to the introduction of force; one felt more inclined to allow nature to do the work, if possible. Although a good deal had been heard about power boost in the American fighters, he would have thought that it could have been kept out of fighters for a bit longer. Whilst it was obvious that we should arrive at a size of aeroplane in which it would have to be used, we ought to get the best that was possible out of the spring tab. The servo control could carry on from the spring tab. Development work on power boost should of course be actively pursued.

With regard to aileron repeatability, there was quite a need for production and design technique to come into line with aerodynamic requirement. Surely these could be improved

to some extent. He wished we could do away with ailerons altogether! The authors had said some disparaging things about weights and springs; but he felt that the weight and spring was a very effective and economical way of achieving stick free stability. The only reason he could see for not using them was so that they could be used when stability difficulties arose.

The horn balance seemed to be invaluable for getting stick free stability, this was often very difficult without it. He asked for Mr. Morgan's comments on trimming tailplanes, as against the tab-trimmed elevator with fixed tail plane. It was not impossible that the trimming tailplane would come back for certain uses in aeroplanes.

Communicated.

The design of controls seemed in the present state of knowledge to be very far removed from an exact science, particularly when nacelles were situated in front of tails.

Summarising the position on forms of balance one might say that there were three main types available for the immediate future:—

The shrouded leading edge (or Irving) balance;

The unshrouded horn;

The tab (geared, spring or servo);

all other types would appear to be washed out on the score of drag and Mach number effects; of the above three the spring tab was the only one which cheats the (speed)^2 law. A judicious mixture of the above three ought to give, in most cases, desirable stability and control characteristics.

We have had unsatisfactory results with convex control contours, they seem, in the present state of knowledge, to give troublesome variations of hinge moment with altitude and to some extent with speed.

Advocates of power boost should remember that there was no magic in it, *i.e.*, it was the aileron which finally does the job: a given rolling performance required approximately a given aileron angle no matter how this aileron angle was produced.

What does Mr. Morgan think about the use of power to produce "ersatz" stability as opposed to inherent stability—the automatic pilot to some extent did this—what economies in control size and weight did this make possible?

Squadron-Leader A. F. MARTINDALE (R.A.E.): He described himself as Mr. Morgan's chief headache, because he was not susceptible to mathematical analysis; and after Mr. Morgan had spent some time getting an aeroplane to his liking on the ground, Squadron-Leader Martindale would take it into the air and would conclude that he did not like it!

He agreed that everything possible should be done to make big aeroplanes controllable by aerodynamic means rather than by means of power controls; but we should do everything possible to push ahead with power controls, for they were bound to come. At the same time, he was very nervous about their first appearance!

In the course of his experience as a test pilot during the last three years he had had about six complete hydraulic failures on undercarriages; in addition, there had been many temporary failures, when he had had to turn the machines upside-down in order to get the wheels down, or had had to shake them down, or possibly reselect several times. Failure did not matter so much in the case of an undercarriage; but any failure of controls, whether permanent or temporary, would be very serious indeed. Therefore, he would like to think that the first aeroplanes with power-operated controls had some alternative system which would enable a pilot to get his machine back home in the event of a power failure. The sooner the power-operated controls appeared, the better, because aeroplanes were still of a size which could be flown on the manual system in an emergency.

The "Lightning" was the only machine he had flown with power-operated controls; it demonstrated that pilots' opinions should not be regarded as unalterable. There was abso-

lutely no "feel" to the controls of that aeroplane, *i.e.*, the force required to move the controls was constant at any speed or displacement. But the machine was not unpleasant to fly, and quite obviously one could get used to new things.

He was one of those who had been questioned by Mr. Morgan about the forces which pilots had to exert, and he agreed with the figures quoted in the paper! But when the control forces were so light it was necessary, of course, to prevent the pilot from breaking the aeroplane, especially during operational flights. When flying a machine with light controls on experimental flights, he felt very nervous unless there were some restrictor to prevent him breaking the aeroplane, especially on unknown types such as German aircraft; the provision of some restrictor would be absolutely necessary where power-operated controls were used. On the other hand, attempts to produce very light controls by aerodynamic means often produced overbalance on production aircraft, whatever system was used.

Mr. J. LANKESTER PARKER (Short Bros.: Fellow): It had seemed to him for many years that one of the greatest problems the designer had to face was that of deciding what an ideal control should do. It was valuable to have a goal at which to aim, and the paper by Mr. Morgan and Mr. Thomas went far towards defining that goal.

He could not from personal experience talk of high speed problems, but there were severe control problems associated with just "largeness." On several occasions he had been concerned with the testing of an aeroplane or flying boat of, say, double the weight of any that was within his previous experience, and he had met with some unexpected problems. He believed the scaling up of an aeroplane to double its previous linear dimensions multiplied the control loads by 8, assuming the same speed, and increased the moment of inertia of the controls something like 32 times. In other words, the load varied roughly as the cube, and the moment of inertia as the fourth or fifth power. If that were so—and experience indicated that it was something of that order—it followed that the aerodynamic balance would have to be greatly increased in order to cope with the increase of size, for the pilot, unfortunately, did not acquire greater size or strength as the size of aeroplane increased, and he did feel rather like an insect when in a large machine. It might be possible, by the application of great cunning, to make the aerodynamic load light enough to enable the pilot to operate really big controls; but nothing had yet been done, or even seemed to be possible, to reduce the amount of inertia of the controls. It might be thought that he was rather over-stressing the matter; but it was important that the actual aerodynamic load should not be completely overshadowed by the other two resistances to motion (mechanical friction and moment of inertia) which a pilot must overcome when moving a control: this will cause a loss of "feel" and prevent rapid application of the control, particularly at low air speed.

He would not pretend to be able to interpret the term "feel," and he agreed with Squadron-Leader Martindale that pilots could learn to use controls in a different way and soon get to like them. Nevertheless, "feel" was a very real thing, and was something we should not dispense with lightly. He believed that a good pilot could fly a completely new aeroplane, one which had never been flown before, without a single instrument in it; there must be some sort of "feel" to enable him to do that.

To render an aeroplane unbreakable merely by making the controls so heavy that the pilot was not strong enough to manœuvre it sufficiently was surely to approach the problem from the wrong angle. It was almost certain that a small or a weak man would find such an aeroplane very heavy to fly. Referring to the motor car for purposes of analogy, he said it had not been found necessary to make the steering so heavy that it was impossible for the driver to turn the car over

when travelling at high speed. However, he agreed that some form of "g" restrictor or reduced control gearing at high speed should be provided, and he believed it could be designed.

Recalling the point made by the authors that when spring tabs were fitted to really large aeroplanes they were no longer spring tabs, but were in fact servo tabs, he said that some years ago he had had considerable experience with rudders of the Flettmer type developed at Farnborough, which consisted of a large tab mounted well behind the main rudder and operated directly by the rudder bar. The pilot had no direct connection with the rudder proper. One of the bigger snags with that type of control, in his experience, arose in the tail-to-wind case; when the aircraft was taxi-ing across wind, and especially when moving down wind, it would swish about all over the place, and turns on the ground had to be made in the direction to avoid "jibing," and it had seemed to him that it was very liable to break.

Finally, Mr. Lankester Parker paid his personal tribute to Mr. Morgan and his colleagues for their extreme helpfulness and patience, whereby they had made very important contributions to the development of British aviation. Without their help, the testing of the larger prototypes would have been considerably more hazardous.

Mr. P. G. Lucas (Hawker Aircraft Co.: Fellow): The subject of control surface design was probably the most difficult from the point of view of the pilots who tried to put their ideas across to the design staffs, and also from the point of view of the design staffs who were trying to understand what the pilots wished to convey to them. That interchange of ideas had been almost impossible in the past, because there were no numerical standards to which the design staffs could design their aeroplanes, nor were there methods of obtaining quantitative measurements in flight. Obviously, for instance, unless the designers knew what rate of roll was required they could not stress the wings to take it; neither could the pilot tell the designer how fast the machine was rolling unless he had some means of measuring it. Therefore, it was important that, in order to achieve a good control development, there must be a limited amount of instrumentation, and some clearly defined numerical standards laid down by the operators of the aircraft.

It was of no use designing an aeroplane which was so strong that it could not be broken or so fast that nothing could possibly go faster, unless it was under the full control of the pilot. Further, an aeroplane could be ruined by general unpopularity, or even its potential operational uses could be nullified, by bad control.

The importance of good test teams, and the desirability for the technical people to have some flying experience and to be able to fly a machine themselves, could not be over-emphasised, for pilots had always spoken a language of their own, and probably would continue to do so; the better the pilot and technician understood each other's language, the closer would be the general understanding between them; and that could be achieved only if the latter had some experience of flying. A glossary of pilots' terms might with advantage be produced, because pilots explained things in a way which it must be difficult for others to understand!

Having had quite a lot of experience of spring tabs recently, Mr. Lucas said that not only did they confer advantages from the point of view of ensuring light stick forces, but that by careful design it could be so arranged that the pilot could not apply a greater control force or movement than the aircraft was designed to take.

The harmonisation of an aeroplane could best be effected by instrumentation and quantitative measurement; but the qualitative side must also come into it. He agreed entirely with Mr. Lankester Parker's remarks with regard to moments of inertia and friction in control surfaces, because qualitative hand-

ling was seriously affected by those two particular matters.

Mr. J. V. Inglesby (Associate Fellow, contributed): The trouble with recent control surfaces appeared to be the uncertainty of their behaviour. Their uncertainty was attributed to small differences in profile, especially near the trailing edge. He wished to point out another possible cause of the trouble—the inboard end of the surface. In almost all designs, the inner end of ailerons and elevators and the lower end of the rudder, in their neutral position, were flush with the static part of the aircraft. This would help to improve the performance when the controls were neutral, but what happened when the surfaces were deflected? Local turbulence was inevitable, and turbulence anywhere was bound to be uncertain in behaviour.

REPLY TO THE DISCUSSION

Mr. Morgan, replying to some of the points raised in the discussion, said he fully agreed that the power operation of controls must come; there was no question of it having to come over his dead body, as it were. He felt, however, that the period during which power operation was being tried out would be a very awkward period for the pilots, as distinct from the technicians; it was very important to provide some plausible alternative to power operation at which a pilot could clutch if the power failed, as fail it might. On the very large aeroplanes the only alternative to power operation which would shove the controls around was the pure servo tab. There was thus a strong case for pure servo tab development as an insurance, during the era of transition to power controls, against the failure of what one hoped would ultimately be foolproof power operation.

For fighters he could not see any case for power operation, at present-day speeds. We might run into sub-sonic and super-sonic regions, in which the controls would go haywire; in this case power operation might well prove to be the only way out.

Technically it was quite feasible for a "g" restrictor to be produced, if it were needed, for the light stick forces that he had advocated. On the other hand, Mr. Lankester Parker's motor car analogy was extremely good. It was possible for a car driver to overturn his car when travelling fast, but motor car drivers just did not do that; they did not haul the steering gear violently when travelling at 60 m.p.h., nor did aeroplane pilots haul on the stick until they were blue in the face. So that, whilst there was an argument for a restrictor, he did not think that in general it was over-strong, although each case would obviously need to be considered on its own merits.

The moving tailplane was very attractive, particularly when dealing with compressibility effects in high-speed dives; it was a most potent means of applying high controlling moments in pitch. He believed the structures people in this country took a very dim view of the moving tailplane and he did not think that its use was encouraged; but it might have to be used on some of the faster machines.

The Fletner tabs, mentioned by Mr. Lankester Parker, were rather like flags hanging out behind the controls. Nowadays servo tabs looked like ordinary trim tabs, and a very large aeroplane in America had been flying for some time with pure servo tabs on all three controls. It seemed to get on quite happily with them, although it weighed about 150,000 lb.

Dealing with the question as to what was the point of all the mighty theoretical work and tunnel activity when we just did not arrive at the complete answers, Mr. Morgan urged that theoretical and tunnel work was well worth while and indeed essential; for example, once we had established what the prototype was doing, it helped us enormously to know what to do next in the way of putting the controls right. If we had to grope around in the dark, without the background of theoretical and tunnel work, the development of controls would occupy a much longer time.

The reasons for the discrepancies were bound up largely with geometry. The hinge moments of highly balanced controls were very sensitive to minute changes of shape, and the designer could not predict the shape of his control from the aerodynamic point of view. He could draw it on paper, but the control just would not look like that from the aerodynamic viewpoint. A small bump on the back end of a control, which one could hardly see, might make it twice as heavy, or it might make it overbalanced.

The reference by Mr. Lucas to a glossary of pilots' terms recalled to his mind an occasion on which a number of pilots and technicians at Boscombe Down had tried to write such a glossary. A highly entertaining document resulted, sprinkled with terms like "nibbling" and "sawing," and abounding in nice distinctions such as that between "shuddering" and " juddering." (Mr. Morgan said that he would reply more fully to the discussion in writing.)

AUTHORS' WRITTEN REPLY TO THE DISCUSSION

We appreciate the opportunity of being able to reply in writing to the discussion following our lecture, since many of the points raised need a more considered opinion than is possible in a verbal reply.

Sir Melvill Jones supported our contention that technical people engaged on stability and control work should learn to fly. We would like to stress this point, since in our view nothing like enough weight has been given to it in the past. His reference to the dangers of wandering off into elaborate mathematics was greatly appreciated. In this field, mathematical analysis is an absolutely essential servant, but it can be a highly dangerous master; in particular we would urge the theoretical worker to keep constantly before him the basic physical assumptions on which his analyses are based—the tenuous nature of many of these assumptions is often overlooked in the delight at exhibiting one's prowess in juggling with the equations.

The case for power operation development was argued by Sir Melvill Jones, and this topic ran through the remarks of most of the subsequent speakers. Our views on the points raised on this subject may be summarised as follows:—

(i) No one questions the advantages of a completely reliable power operation scheme. The discussion centres around the problem of reliability—what happens when something goes wrong?

(ii) For extremely high speed small aircraft, which have to operate in high subsonic or supersonic regions, there is an overwhelming case for urgent power operation development. One feels instinctively that a power-operated all moving tail plane is a sound approach. The reliability problem is slightly eased by the fact that, on aeroplanes of this class, it may prove possible so to arrange matters that direct manual control is within the physical compass of the pilot at low speeds and modest Mach numbers, so that a successful landing could be made in the event of power failure provided the pilot was lucky enough to regain control at low altitude.

(iii) For very large, but relatively slow speed aircraft, there is a strong argument for power operation, provided the system is such that mass balance of the control surfaces can be dispensed with. In this case, however, a very plausible alternative exists in the pure servo tab. Were it not for the weight of mass balance involved with a servo tab scheme, the case for power operation would, in the authors' opinion, be far less convincing, at least on aircraft up to 500,000 lb. all-up weight (it should be borne in mind that, being aerodynamicians, we are, of course, biassed). On these very large machines, reliability is all important, since once committed to power the controls will be unmanageable without it; it is on this count that the pure servo tab scores so heavily.

(iv) It is of the utmost importance that power operation schemes should be very thoroughly tested on aircraft of modest size,

which are manageable on manual control when power fails, before designers commit themselves to power on the really big machines. To go straight to power on the large aircraft without extensive tests in flight on the small machine would seem a gamble. The argument that all necessary development can be undertaken in a ground rig is, in our opinion, highly suspect.

(v) Many of the difficulties encountered in power-operation schemes to date arise from the prevalent opinion that "feel" should be provided by feeding back to the stick a proportion of the aerodynamic load on the control surface. In our view this refinement is completely unnecessary on very large aircraft; adequate "feel" can be provided artificially by springs to give self-centring, with, if necessary, a subsidiary device to increase control weight with airspeed; a "g" restrictor can be included if harsh use of the elevator is feared. It is felt that designers of power control units for large machines would have a far clearer run, and would be faced with fewer development difficulties, if the idea of feeding back "feel" from the unit was abandoned at the outset.

In reply to Mr. Ellis and Mr. Page, who asked for information on the possibility of a reduction in the rather crippling amount of mass balance which must be carried around with spring and pure servo tab designs, the application of irreversible and damper mechanisms immediately comes to mind. Much thought is rightly being put into such an approach, but in our view a more profitable line of attack would be a fundamental investigation in each particular design of the flutter characteristics of the spring or pure servo tab system proposed, undertaken by a competent flutter team. In many cases it may well be shown that, provided the weight and inertia of the tabs were made very small by clever layout and construction, there would be no necessity to mass balance the tabs at all. This would remove the major portion of the mass balance incubus, since when a tab is mass balanced a lot more lead has to be added ahead of the main control hinge to retain mass balance of the main surface.

Mr. Ellis also raised the question of aerodynamic boosters. There was no intention of brushing these aside hastily, although this impression may have been given owing to the limitation of time during the verbal delivery of the lecture. Possibly a major application of this sort of gadget will be the provision of suitable artificial "feel" when used in conjunction with irreversible power operation on large aircraft.

Mr. Rowe raised the question of the utility of theoretical and wind tunnel work on control hinge moments, when in real life an empirical hit-or-miss process seems usual in getting the controls of a prototype right, and suggested that larger tunnels might be a help. The tunnels and theory do in fact provide the designer with an essential datum from which to work in proportioning his controls. The major difficulty of sensitivity to minute geometrical differences would be eased if the actual control, as manufactured in the shops, could be tested at a reasonable speed in a tunnel large enough to take it; such tunnels are, however, expensive. An approach which appeals to the authors is to test the proposed new controls for a prototype in flight on a smaller aeroplane. For example, if a firm is building an aircraft somewhat larger than their former production type, the complete tail plane and elevator of the new machine could be manufactured in advance, full size, then fitted to an existing smaller aircraft—which would be purely a test bed—and flown. This would be quite feasible, although the tail would be oversize for the test aircraft, by suitable ballasting. With appropriate instrumentation, much of the development work on the hinge moment characteristics of the new tail could be undertaken in this way before the prototype actually flew. Fin and rudder development could be undertaken in a similar manner. In many cases such a policy would, if decided on at the outset, save a lot of time and trouble.

The subject of standards of control for civil aircraft as compared with those for military machines was also raised by Mr. Rowe. Undoubtedly very different standards are needed, with emphasis sharply on safety and with less attention given to extreme manœuvrability at high airspeeds. A dangerous argument often heard is that the civil pilot will be far more highly trained and tightly controlled than the Service pilot. There is a temptation to use such an argument to excuse oneself from improving some handling characteristic—"it would never catch out a civil pilot." Now the best of pilots have their off days, and we feel strongly that, compared with military designs, as much or even more effort should, on civil machines, be put into making the handling characteristics such that the consequences of the pilot doing the wrong thing are as innocuous as possible.

With regard to Mr. Rowe's point about cleanliness, controls *can* be made clean (*e.g.*, sealed balance, internal linkages, etc.); we have no doubt that on civil types, where economic operation is vital, this problem will look after itself.

Dr. Cameron asked for our views on "g" restrictors, a topic also touched upon by Mr. Lankester Parker and S/L Martindale. On largish aircraft, provided the stick force needed to break the aeroplane exceeds 100 lb. from the trimmed condition, we feel that the necessity for a "g" restrictor is doubtful. With power operation, however, pilots may well far prefer a very light "feel" for general flying, which would give a force far below 100 lb. for breaking "g." In that case some form of restrictor, pre-loaded so as to leave the "feel" for ordinary manœuvres unaffected, would be highly desirable, if not essential. It is safe to say that, with our present knowledge, production of a suitable restrictor is technically quite feasible.

The question of large changes of directional trim with speed and power was also raised by Dr. Cameron. Contraprops and jets both provide the complete answer. Without them it is difficult to see any single approach to a satisfactory answer for the region of high powers and very large airscrews into which we have run; each case must be treated on its own merits. Two tricks, which were not mentioned in the lecture, may provide a useful lead in certain cases:—

(i) Separate fixed tabs on the rudder, bent outwards in different directions, one in the high velocity slipstream region and one outside it. If the hinge moments of the tabs about the rudder hinge are just balanced engine-on, they will obviously be unbalanced on throttling back, since the tab in the slipstream will lose effectiveness whereas the tab outside will be unaffected. This lack of balance can be arranged to move the rudder automatically in the direction needed to maintain trim.

(ii) A spring loaded tab on the rudder, offset 10° or so. As speed is increased the tab will blow back on the spring. By suitably adjusting tab hinge moments and spring strength, this movement can be made to approximate to that needed to maintain trim over the speed range.

Mr. Clarkson commented on our rather harsh remarks about the use of springs and weights for improving stick free longitudinal stability. The tongue was in the cheek when these remarks were penned. Springs and weights are such useful dodges when in a tight spot with instability on a prototype, that it seems a wise policy to keep them up one's sleeve, and never to incorporate them in a design at the outset. He also asked for our views on trimming tail planes—moving planes as compared with tab trimmed elevators. As already mentioned, moving tails may well be essential for high Mach number work. Even for normal machines, however, there is aerodynamically a lot to be said for trimming by moving the "fixed" tail plane. By suitable design it enables one to get away with a very small elevator, which helps to offset the extra weight entailed in the trimming mechanism.

It should be noted that Mr. Lankester Parker and Mr. Lucas, both test pilots of exceptional experience, stressed the import-

ance of good mechanical design of the control circuit.

The suggestion made by Mr. Lucas for a glossary of pilots' terms might be useful, but an argument can be made against it, in that it might encourage the notion prevalent amongst some technicians that a pilot is a special and rather inapproachable being with a language all of his own. Instead of shutting himself up in a box with a slide rule, and consulting the suggested "dictionary" when flight reports arrive in the in-tray, the technical man should spend a lot of time with the pilots, getting their stories direct—the written report being mainly for record purposes. If he is on speaking terms with his pilots, a glossary of their jargon should be unnecessary.

In reply to Mr. Inglesby, who raises the question of turbulence at the discontinuity between the inboard end of a deflected aileron and the undeflected trailing edge of the inner wing, there is little evidence that flow through this gap results in any noticeable vibration or buffeting troubles. Severe buffeting has been experienced when a badly faired protuberance on the wing undersurface ahead of the aileron sends an irregular wake washing over the control. In the case of Frise ailerons bad vibration can be produced in this way even if such a wake extends over only a very small part of the aileron span.

CORRESPONDENCE

VALUE OF WEIGHT SAVING IN AIR LINERS.

To the Editor.

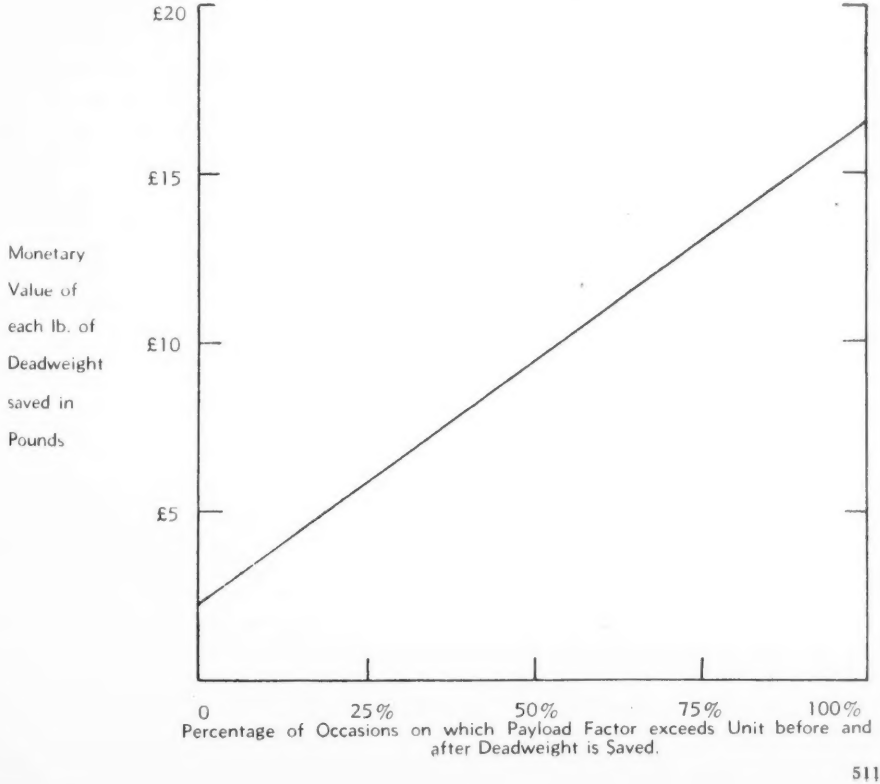
15th May, 1945.

Dear Sir,—With reference to the invitation to correspond upon the above subject, contained in the "Journal of the Royal Aeronautical Society" of April, I submit the following:—

Both Major Green and previous writers on this subject appear to have omitted to recognise the fact that if the payload factor is less than 100 per cent., conversion of some of the deadweight into extra payload capacity will not result in any more payload being carried, because the payload offered is already less than the capacity of the aircraft prior to its having been improved in design. I "fell into this trap" when making a few remarks on this subject during the R.Ae.Soc. discussion on Civil Aviation in November last.

It is only on those occasions when the payload offered exceeds the aircraft's capacity (a payload factor greater than 100 per cent.) that an increase in the plane's payload capacity through weight saving, will result in more payload being carried.

It is only on those occasions therefore that the extraordinarily high economic value of weight saved calculated by earlier writers and suitably whittled down by Major Green can in fact be achieved.



On all other occasions—when the payload factor is less than 100 per cent.—the only economy resulting from elimination of deadweight, is that of fuel saved due to flying at a lesser all-up weight than would otherwise be the case.

From calculations supplied by a colleague the value of weight saved under these circumstances is a fraction of the figure finally arrived at by Major Green, just as his result is a fraction of the American author who suggested that a pound of deadweight saved was "worth its weight in gold."

Using Major Green's figure of 3,000,000 total miles flown, and the price of fuel as 2s. per gallon, and assuming that the aircraft is never offered more payload than it could carry prior to improvement, the value of each pound of deadweight saved is then of the order of only £2 5s. 0d. per lb. There will, of course, be occasions when the payload factor exceeds 100 per cent., but I have been unable to obtain any statistics to show how frequently this occurs when the average factor is 60 per cent.

I therefore attach hereto a graph showing the value of each pound of deadweight saved, between the two extremes of the payload factor never reaching 100 per cent., and of its never being less than this desirable figure. I have used Major Green's tentative figure of £16 10s. 0d. per lb. both for the latter case and for the determining intermediate values.

It must be appreciated that the figure of £2 5s. 0d. per lb. included herewith is necessarily approximate also, as opportunity does not exist for a thorough investigation into this figure.

The foregoing is submitted in order to show the desirability of the aircraft operator attempting to forecast to the designer the percentage of occasions on which the payload factor will exceed 100 per cent. in order to give him a lead as to the economic values he has to consider when attempting reduction in deadweight.

I look forward to the pleasure of receiving some comments upon the principle on which this note is based, in due course.

Yours truly,

E. C. GARRARD.

REVIEWS

To-morrow's Airliners, Airways and Airports.

S. E. Veale. Pilot Press, Ltd., London. 1945. 15/- net.

Only the very bold or the very young can have the temerity—if temerity be the right word—to prophesy in writing what the future holds forth in the air.

The progress of science outstrips the greatest figments of imagination. The prime mover of to-day is obsolescent to-morrow. At the beginning of 1939 few people (and they were labelled fanatics by the many) saw an end to the reciprocating engine as the prime mover for aircraft. By 1942, however, it had become abundantly clear that a new prime mover was speeding into first place and experts were predicting the end of the reciprocating engine as far as aircraft were concerned. The experts were more than a little disturbed when the first V1 was examined, and much disturbed after an examination of the V2. Their ideas which had rocketed skywards with the advent of jet propulsion began to soar towards controlled rockets, and the moon was even considered as a possible landing ground. Before the tumult of the rocket had died away the successful development of the atomic bomb was announced and the experts began a fresh series of prophecies.

This is by way of saying that the way of the prophet is becoming a more increasingly difficult one to follow. Mr. Veale's book might be obsolete before it is written, for he had only got as far as jet propulsion and gas turbines, of which he says that its application to aircraft will mark one of the biggest milestones in the history of aeronautical engineering. (Why one milestone is bigger than another the reviewer is not clear.)

On present-day practice, as apart from present-day knowledge, Mr. Veale's book is, however, by no means obsolescent. He deals largely with the next five to ten years. To quote from his book, "We now begin to see the pattern of to-morrow's air liners. The form they will take during the first five years from the end of the war can be sharply drawn and all the details added. Those of the second five years must be sketched with a lighter touch and finished in less detail. The third five-year period can already be drawn in outline, but gaps may have to be left here and there for shapes of things unknown."

The jet, the gas turbine, the rocket and atomic energy will all have their teething troubles and the enthusiasm of to-day will have to give way to the cold douche of to-morrow's commercialism. Ideas leap ahead of practical progress and it may be more than five years before many of the ideas of to-day come into general use. During that five-year period Mr. Veale should count upon his book being of considerable use. He covers a wide landing ground, covers it in a pleasantly written way, and leaves one with the feeling that he has taken considerable trouble to get his material. It is well worth buying and studying by all those interested in civil aviation and its very uncertain future.

Aviation.

H. E. Wimperis, C.B., C.B.E. Oxford University Press. 1945. 3/6 net.

This is No. 195 of that most excellent series the Home University Library of Modern Knowledge.

Mr. Wimperis has every qualification for being chosen to write this volume. As the first Director of Scientific Research at the

Air Ministry during those most critical years 1925-37 upon him rested heavily decisions, the successful results of which were shown in 1939-1945. Successful lines of research and development must depend upon vision as well as engineering or scientific knowledge, for they depend upon a foresight of what will be wanted in five to ten years time, irrespective of what is happening now. Greater credit than has yet been given must be awarded, therefore, to these aircraft designers, research workers and others, among whom Mr. Wimperis was a leading figure, who had the vision and the courage to lay down lines of development which did not always appear at the time to be too fruitful of results. The decisions were all the more courageous in that the Government itself were parsimonious almost to starvation point, and every penny had to be considered as being likely to bring back three-halfpence before it could be invested in research or development projects.

Mr. Wimperis is kind in saying that "Governmental aid is almost always forthcoming, not merely for the carrying out of researches but for the subsequent application of results which show promise." His chapter, however, on research is one of absorbing interest, from the foundation of the A.R.C. in 1909 to astonishing development of Radar, which, as Director of Scientific Research, Mr. Wimperis had specially directed the attention in 1935 of Mr. R. A. (later Sir Robert) Watson-Watt, for all defence purposes as urgently needing attention.

The scope of this book is adequately shown by the chapter headings, The Growth of Flying; The Research Endeavour; Flight and Physiology; The Airplane in War; Civil Aviation and Aviation in Relation to World Security. The author puts his material into the simplest form, and puts it too, in an easy flowing way which is the sign of careful thought.

The last words in the chapter on Aviation and World Security should be pondered over by everyone who looks into the future. "The scientist and the engineer by their labours have discovered new tools and will assuredly discover many more; to ensure that such inventions shall be rightly used, though vital, is not a task to be imposed on the discoverers alone; *it is the responsibility of all citizens.*"

The italics are the reviewers. The aeroplane and its future is the responsibility of all citizens, and as many of those citizens as possible should buy this exceedingly cheap and informative summing up of aviation as it is at the present day.

As a tailpiece to this review, the reviewer is glad to note how often the author quotes from lectures given before the Royal Aeronautical Society and the opinions of leading members of the Society, for which Mr. Wimperis himself has done so much.

AN APPRECIATION

The Council of the Royal Aeronautical Society wish to thank the following Companies who, by their generous co-operation, have done so much to help in the production of the Journal in its new form.

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Printed by the Lewes Press (Wightman & Co., Ltd.), Friars Walk, Lewes, England, and Published by the Royal Aeronautical Society, 4, Hamilton Place, London, W.1, England.